

High-Energy Nuclear Collisions and the QCD Phase Structure

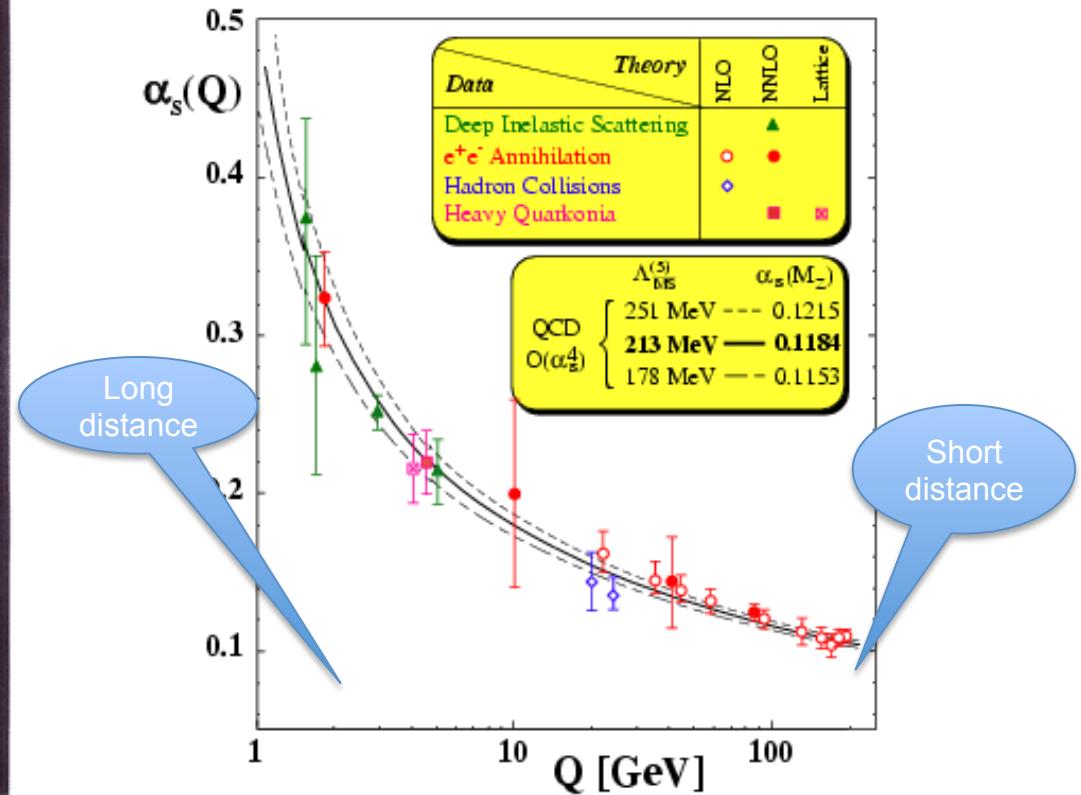
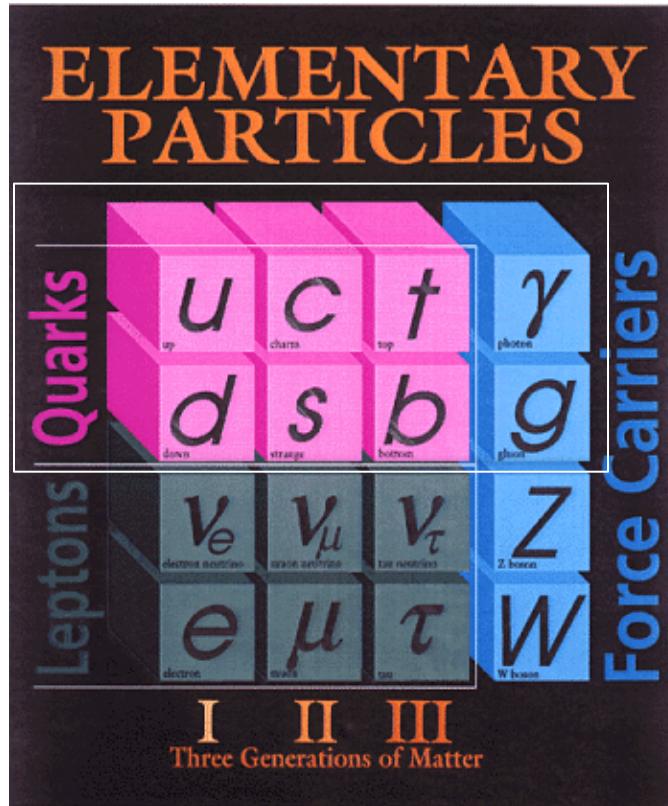
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⁽²⁾ College of Physical Science & Technology, Central China Normal University, China



Quantum ChromoDynamics



- 1) QCD is the basic theory for strong interaction. Its degrees of freedom are well defined at short distance.
- 2) Little is known regarding the dynamical structures of matter that made from ***q, g***. E.g. *the confinement, nucleon spin, the QCD phase structure*... Large α_s and strong coupling – QCD at long distance.

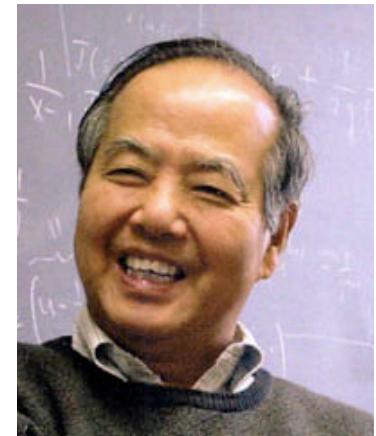
An Approach to Address the Problem

- The confinement:

Quarks are the basic building blocks of matter.

No free quarks are seen, confined within hadron:

$$\Delta v_0 \sim 1 \text{ fm}^3, \quad \rho_0 \sim 0.16 \text{ fm}^{-3}, \quad \varepsilon_0 \sim 0.15 \text{ GeV/fm}^3$$



- Heavy ion collisions: Large, hot, and dense system

$$\Delta v \sim 1000 \text{ fm}^3 = 1000 v_0$$

$$\rho \gg 3 \text{ fm}^{-3} \sim 20 \rho_0$$

$$\varepsilon \gg 3 \text{ GeV/fm}^3 \sim 20 \varepsilon_0$$

T.D Lee, 1970

Quark Gluon Plasma (QGP)

↗ **QGP: Quarks and gluons are ‘freely’ moving in a large volume**

New form of **matter with partonic degrees of freedom**

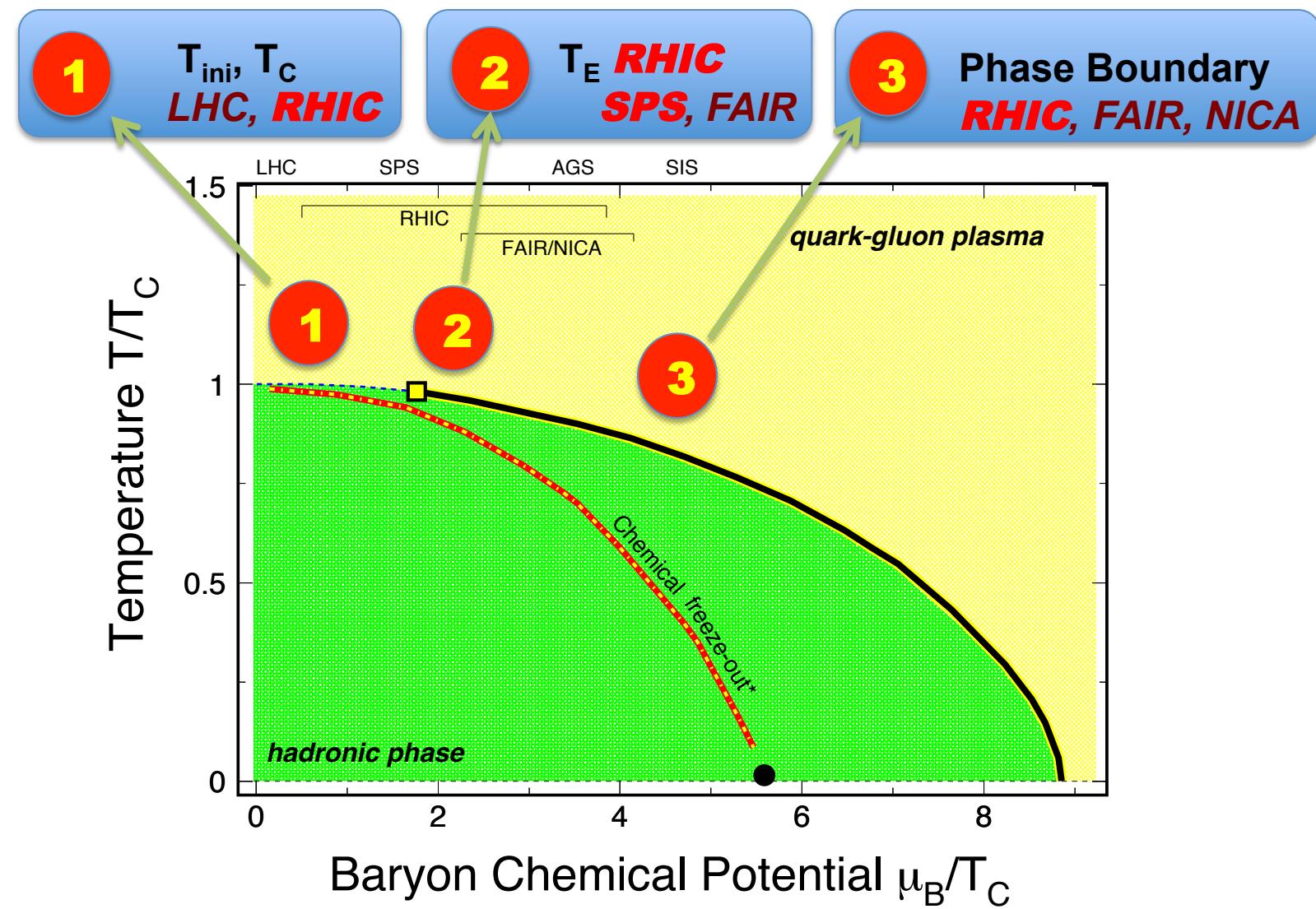
↗ **QCD Phase Structure**

- Connection with other fields

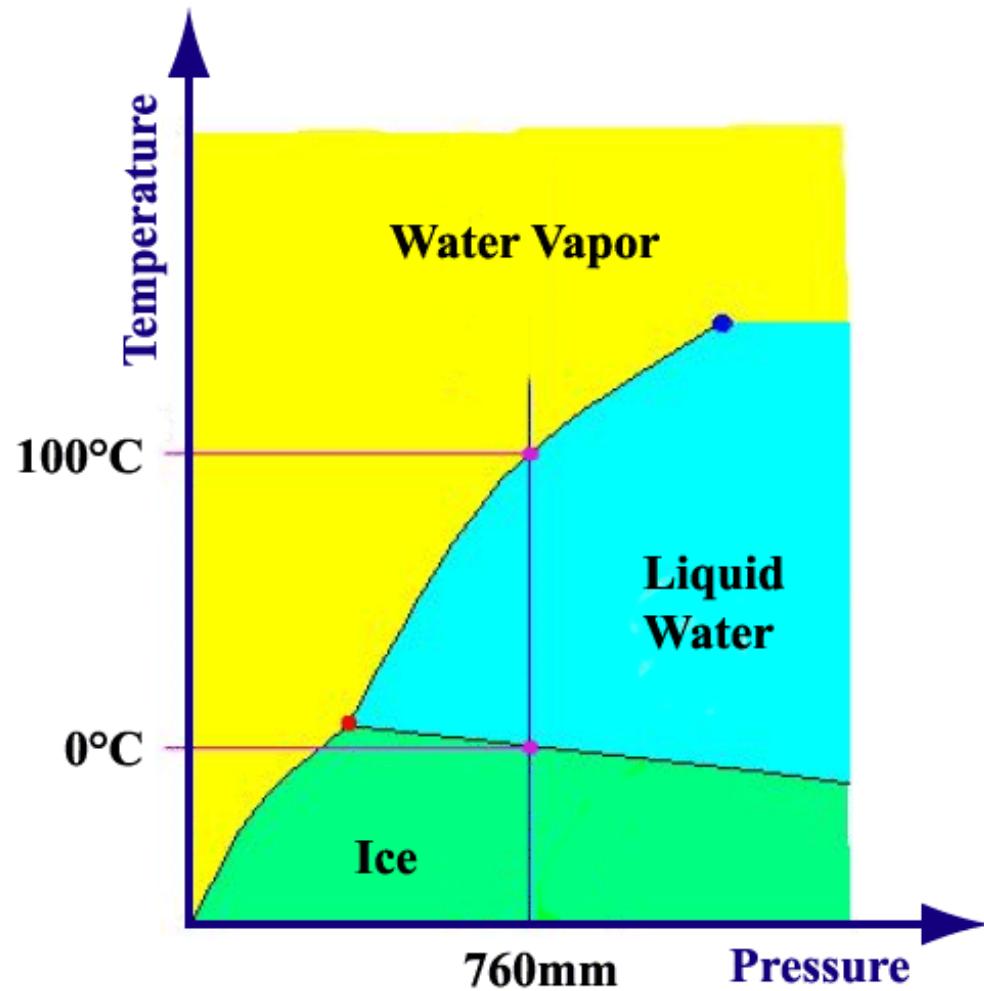
cosmology, origin of the universe, evolution of the universe

quantum statistics with partons

The QCD Phase Diagram and High-Energy Nuclear Collisions



Phase Diagram: Water



Phase diagram: A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

Water: H_2O

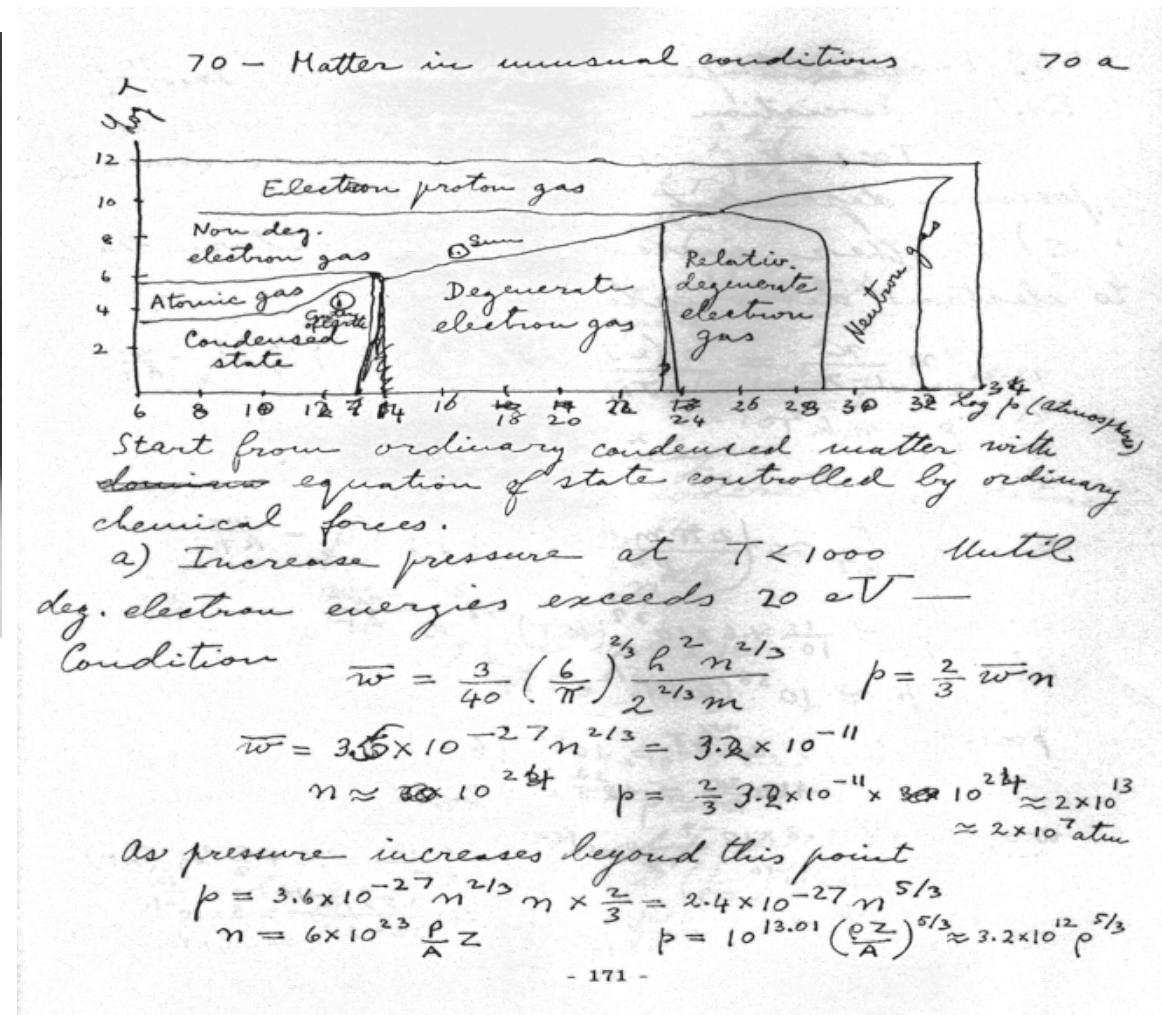
The QCD phase diagram: structure of matter with quark- and gluon-degrees (color degrees) of freedom.

QCD Phase Diagram (1953)



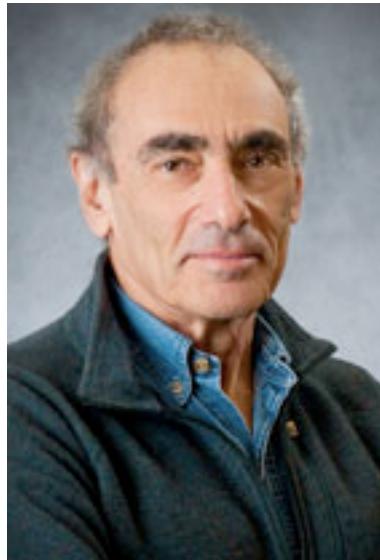
E. Fermi

E. Fermi: "Notes on Thermodynamics and Statistics" (1953)

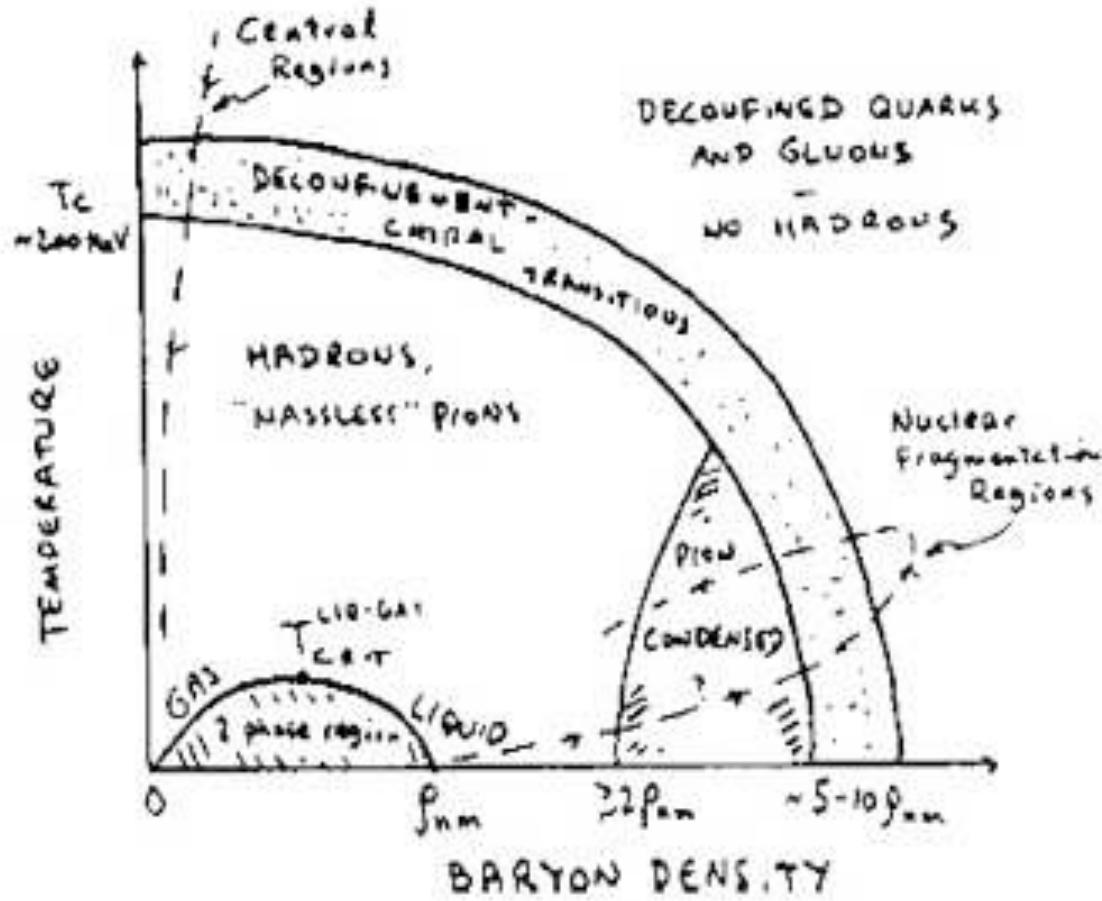


QCD Phase Diagram (1983)

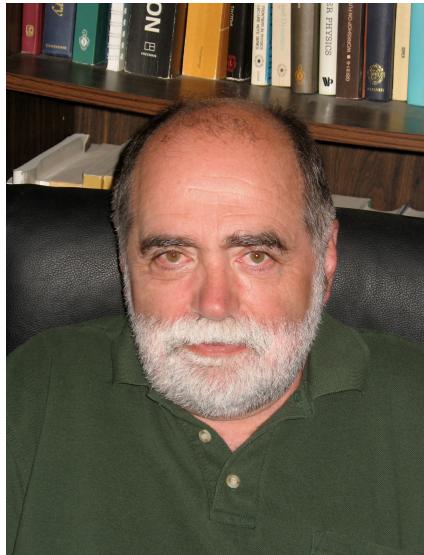
1983 US Long Range Plan - by Gordon Baym



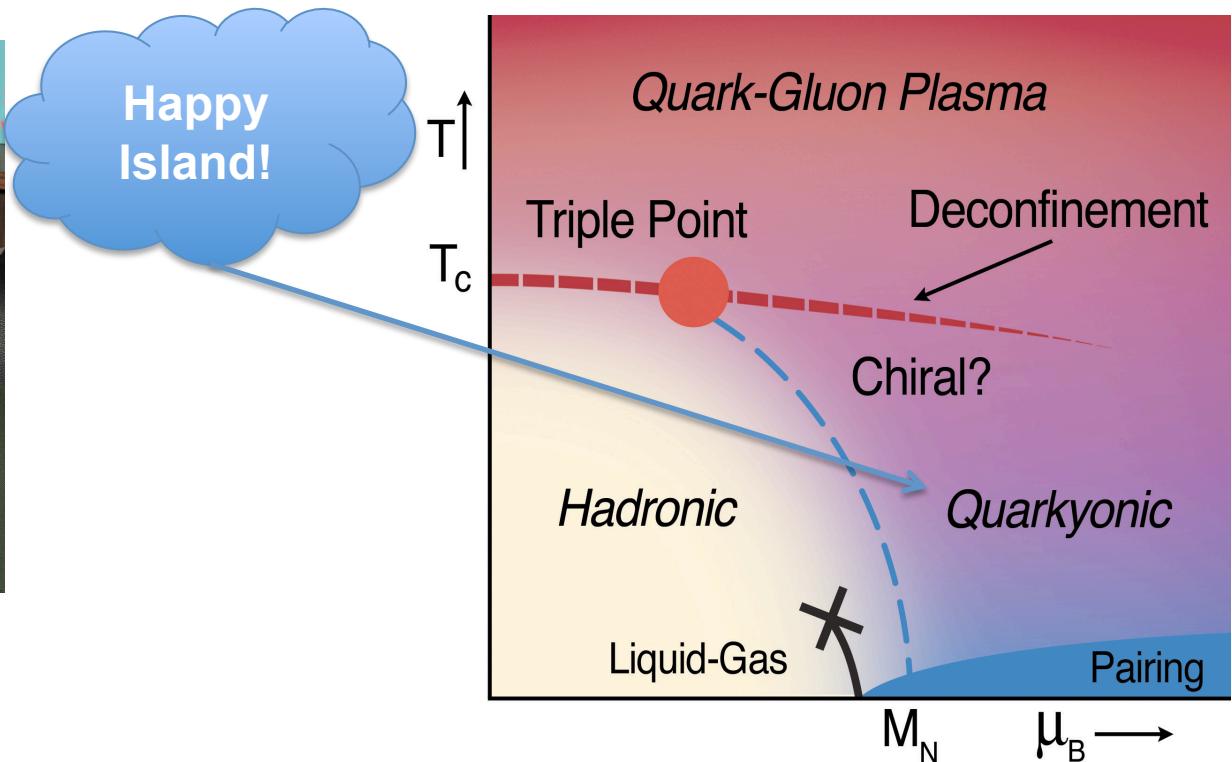
Gordon Baym



QCD Phase Diagram (2009)



Larry McLerran



[nucl-th: 0907.4489, NPA830,709\(09\)](#) L. McLerran

[nucl-th 0911.4806: A. Andronic, D. Blaschke, P. Braun-Munzinger,](#)

[J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler,
R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, and J. Stachel](#)

Experiments: Systematic measurements (E_{beam} , A_{size}) :
to extract **numbers** that are related to the **phase diagram!**

Outline

(1) Introduction

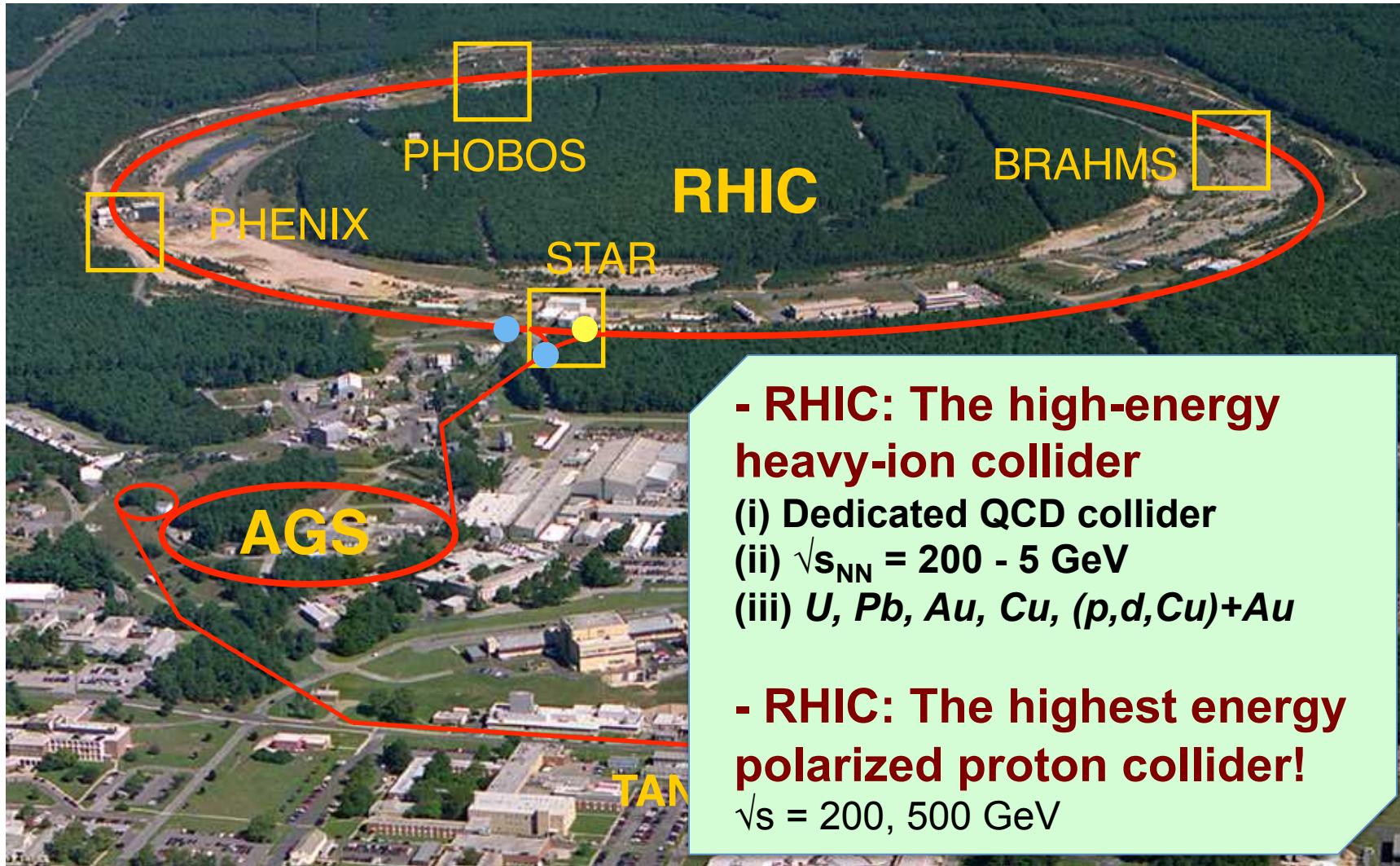
(2) Recent Results from RHIC

(3) RHIC Beam Energy Scan

(4) Summary and Outlook

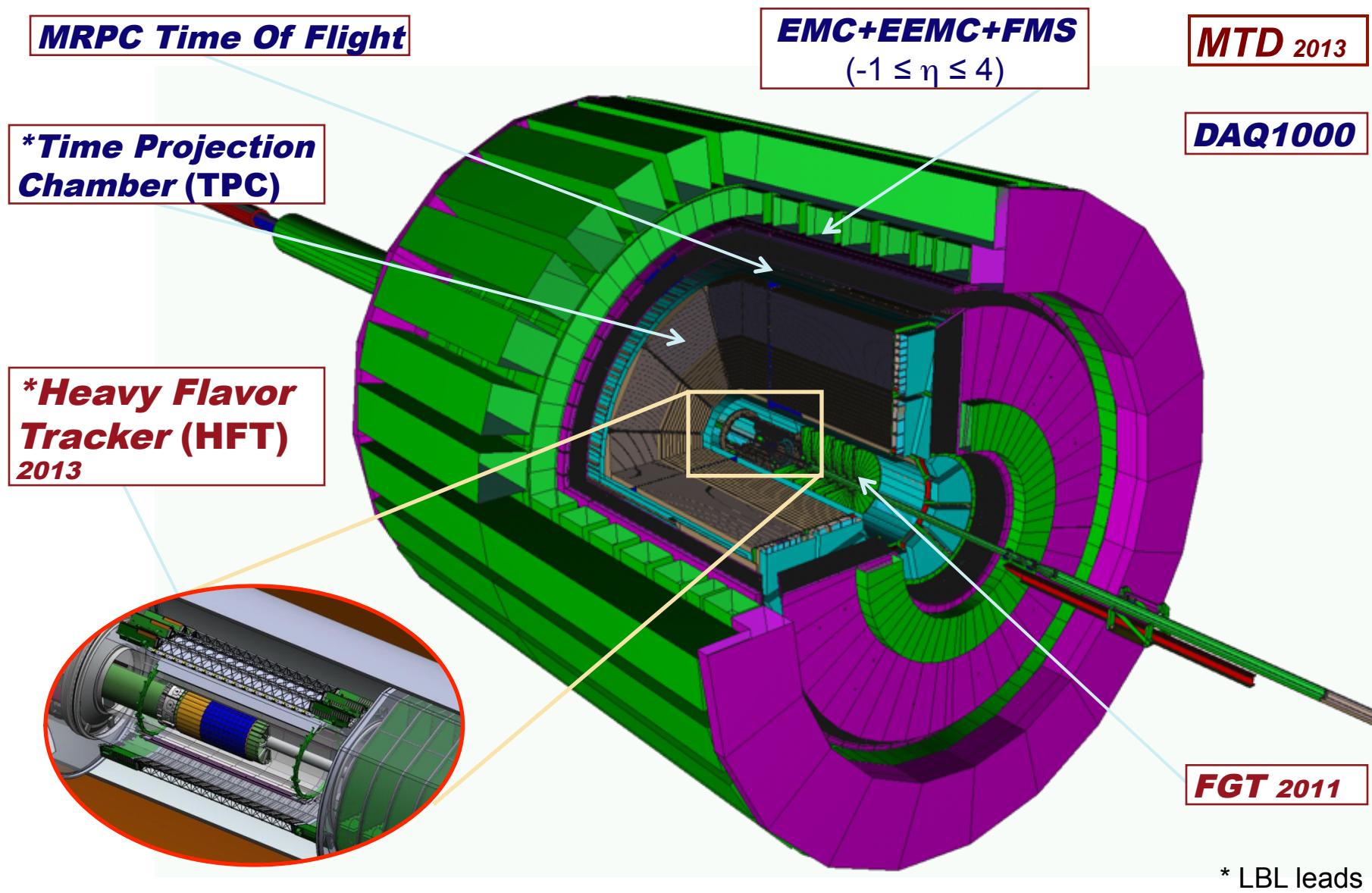
Relativistic Heavy Ion Collider

Brookhaven National Laboratory (BNL), Upton, NY



Animation M. Lisa

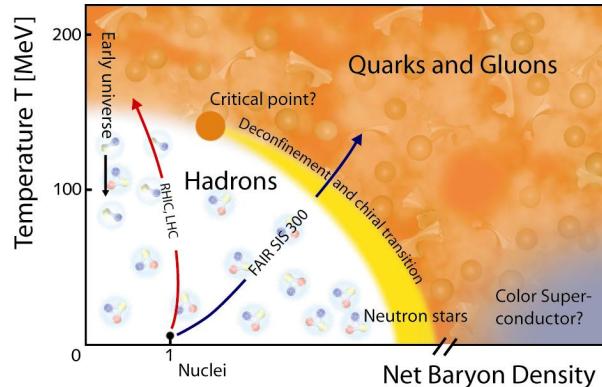
STAR Detectors *Fast and Full azimuthal particle identification*



STAR Collaboration



RHIC Physics Focus

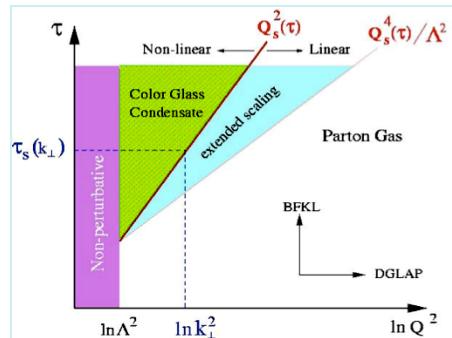


1) At 200 GeV top energy

- Study **medium properties, EoS**
- pQCD in hot and dense medium

2) RHIC beam energy scan (BES)

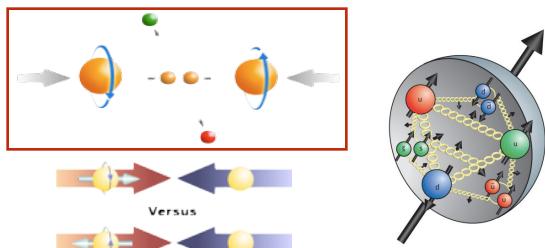
- Search for the **QCD critical point**
- Chiral symmetry restoration



Forward program

- Study low- x properties, initial condition, search for **CGC**
- Study elastic and inelastic processes in pp2pp

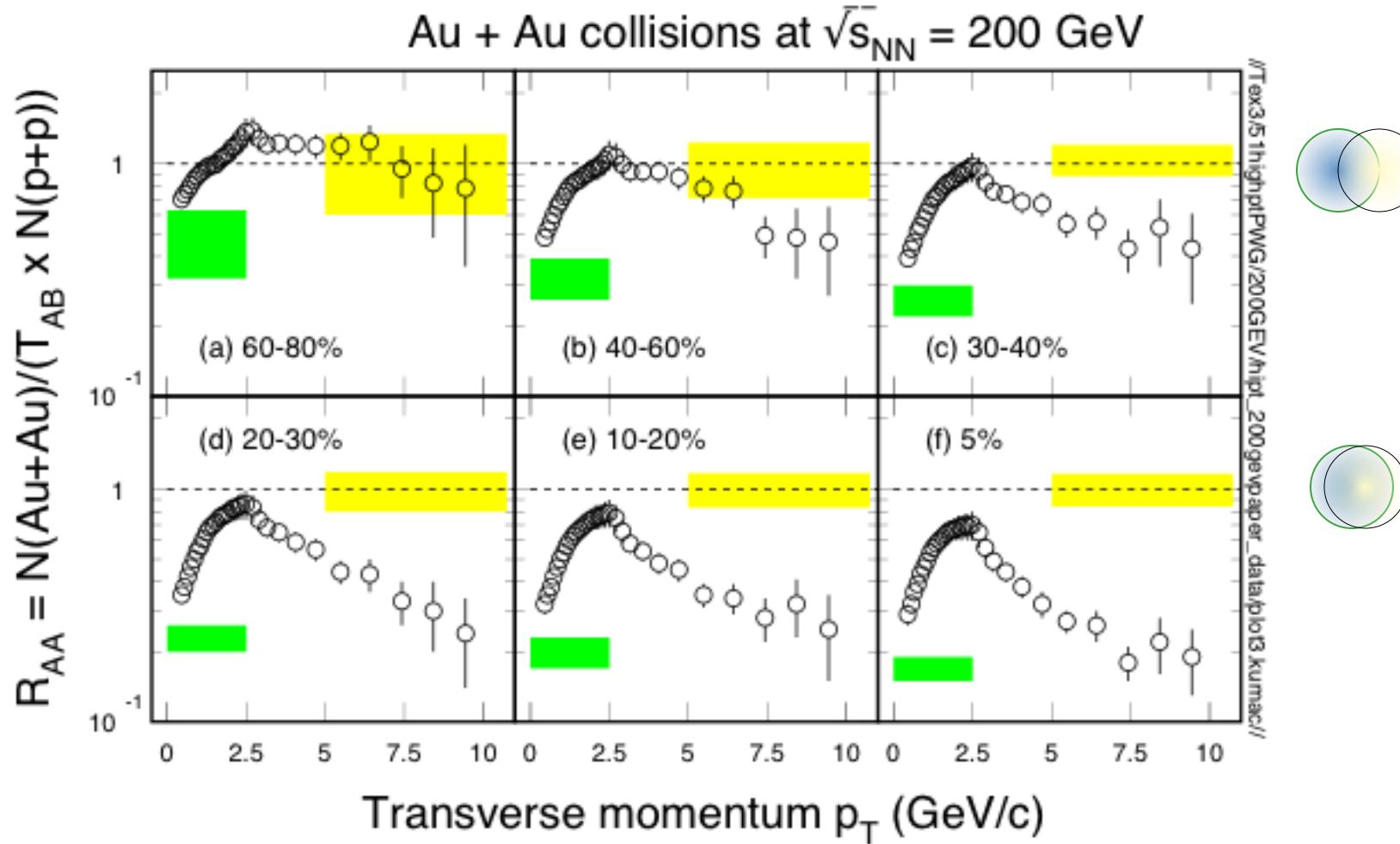
2020 -
eRHIC
(eSTAR)



Polarized $p+p$ program

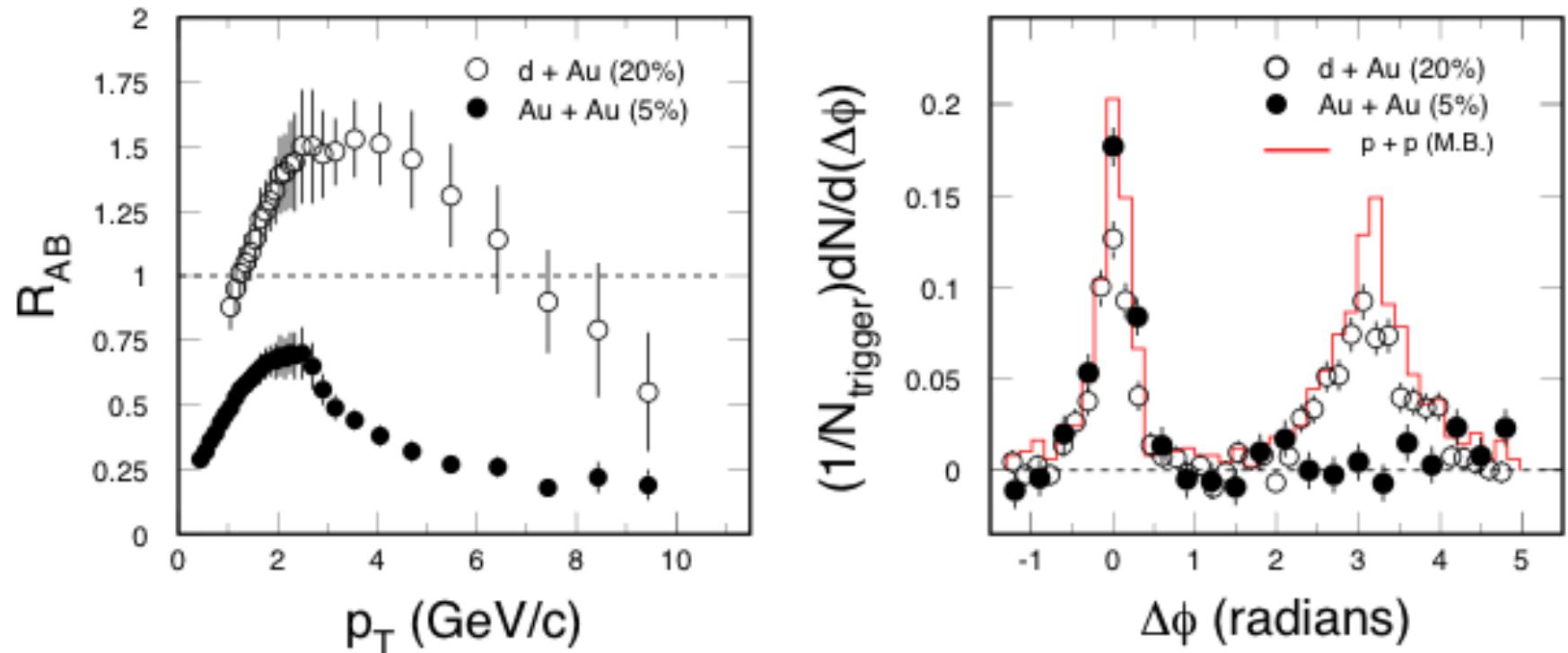
- Study **proton intrinsic properties**

Hadron Suppression at RHIC



Hadron suppression in more central Au+Au collisions!

Suppression and Correlation



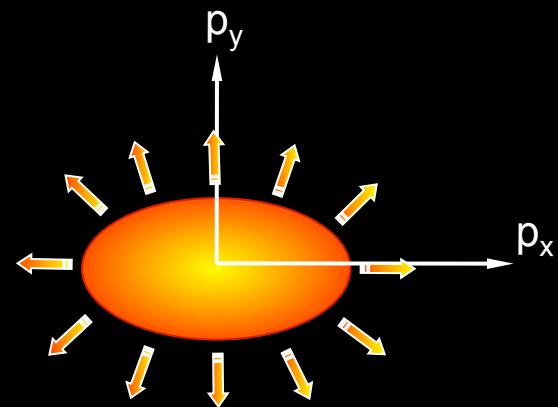
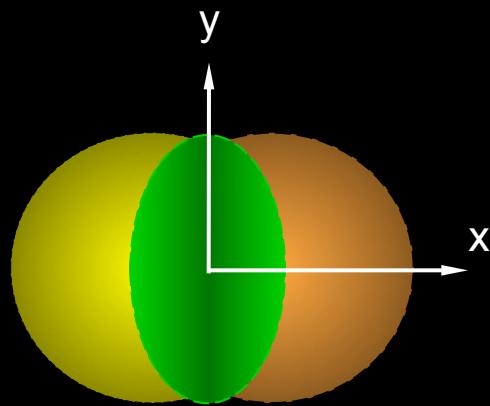
In central $\text{Au}+\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV: light quark hadrons and away-side jets are suppressed.

Energy density at RHIC: $\varepsilon > 5 \text{ GeV/fm}^3 \sim 30\varepsilon_0$

Anisotropy Parameter v_2

coordinate-space-anisotropy

↔ momentum-space-anisotropy

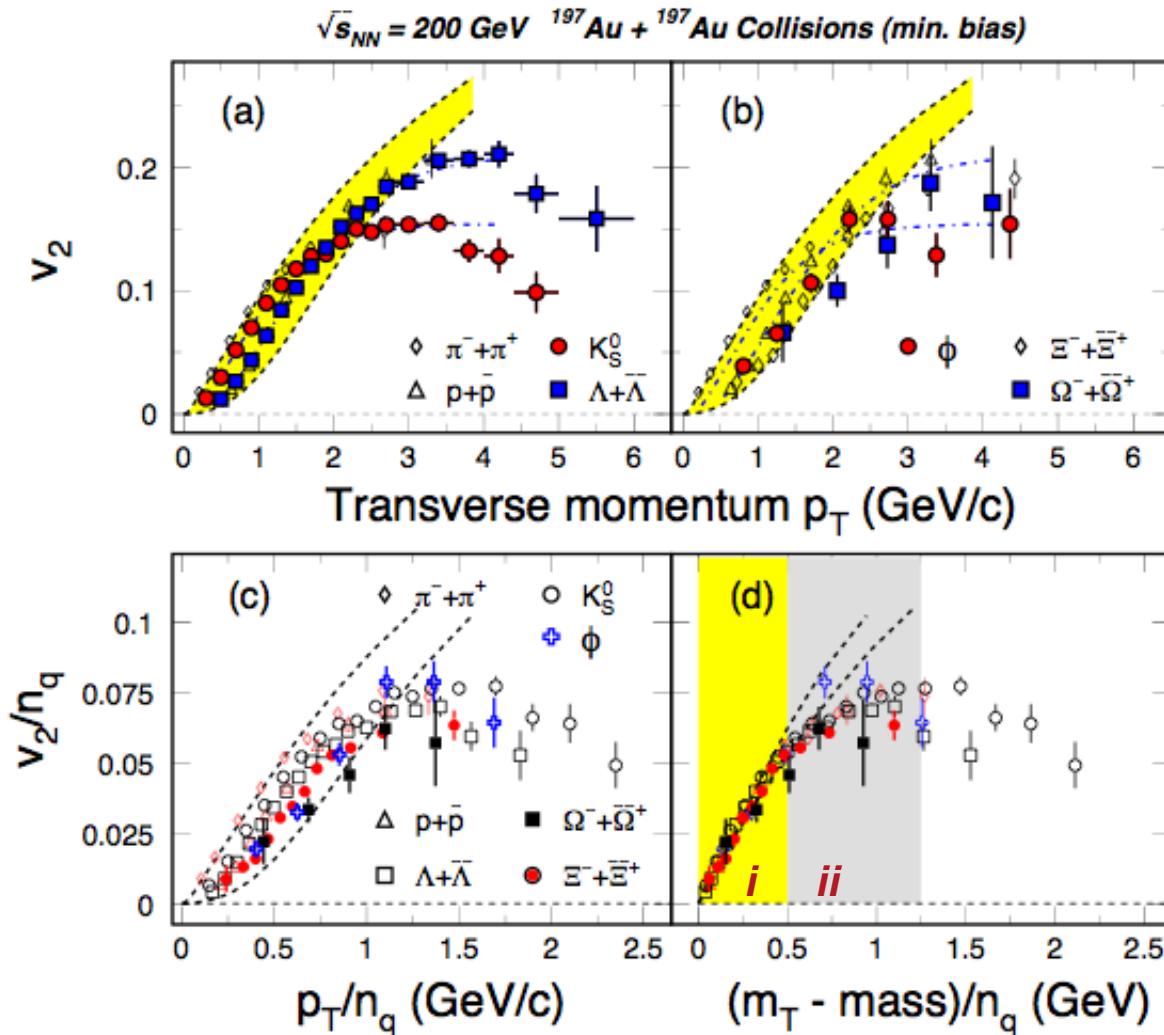


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1} \left(\frac{p_y}{p_x} \right)$$

Initial/final conditions, EoS, degrees of freedom

Collectivity, Deconfinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

⇒ **m_T - NQ scaling**

⇒ **De-confinement**

PHENIX: *PRL* **91**, 182301(03)

STAR: *PRL* **92**, 052302(04), **95**, 122301(05)
nucl-ex/0405022, *QM05*

S. Voloshin, *NPA* **715**, 379(03)

Models: Greco et al, *PRC* **68**, 034904(03)

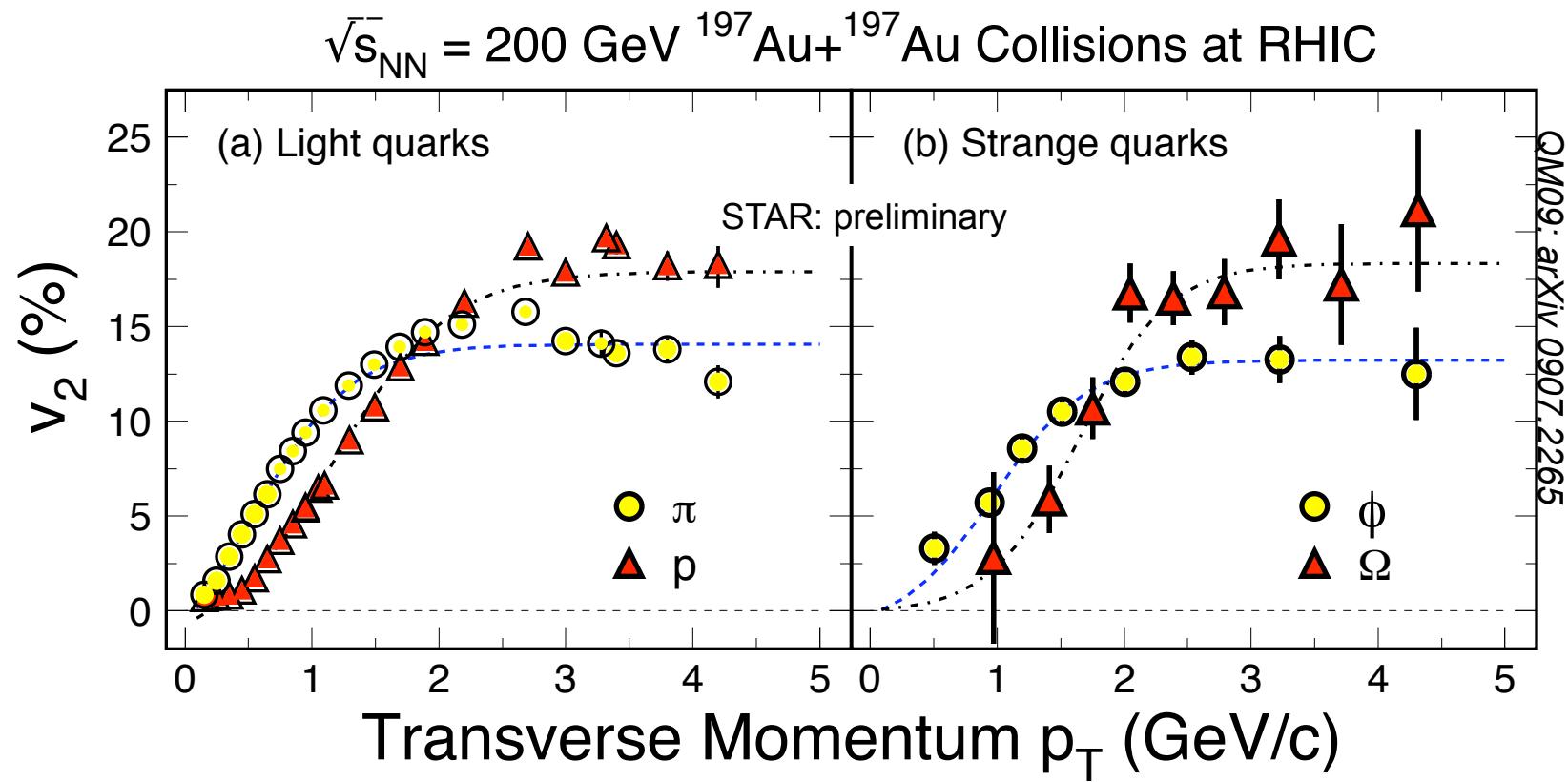
Chen, Ko, *nucl-th/0602025*

Nonaka et al. *PLB* **583**, 73(04)

X. Dong, et al., *Phys. Lett.* **B597**, 328(04).

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Partonic Collectivity at RHIC



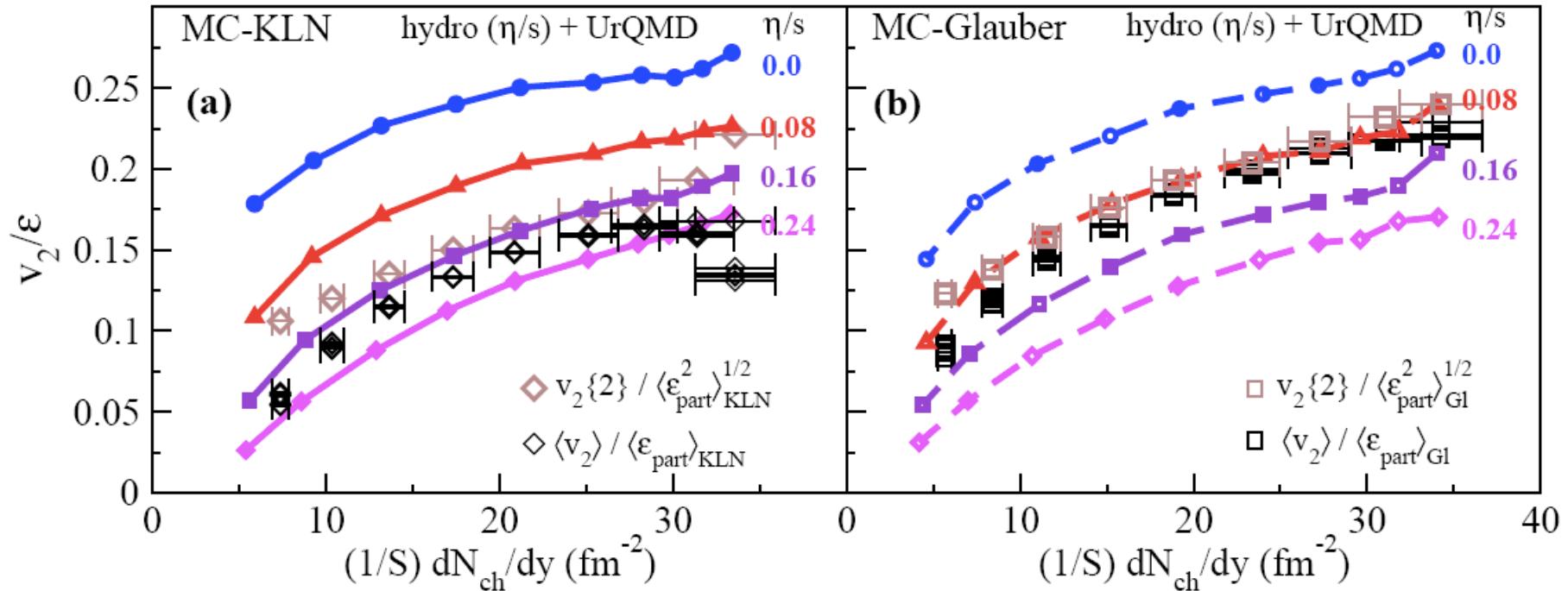
Low p_T ($\leq 2 \text{ GeV}/c$): hydrodynamic mass ordering

High p_T ($> 2 \text{ GeV}/c$): **number of quarks scaling**

→ **Partonic Collectivity, necessary for QGP!**

→ **De-confinement in Au+Au collisions at RHIC!**

Comparison with Hydrodynamic Model



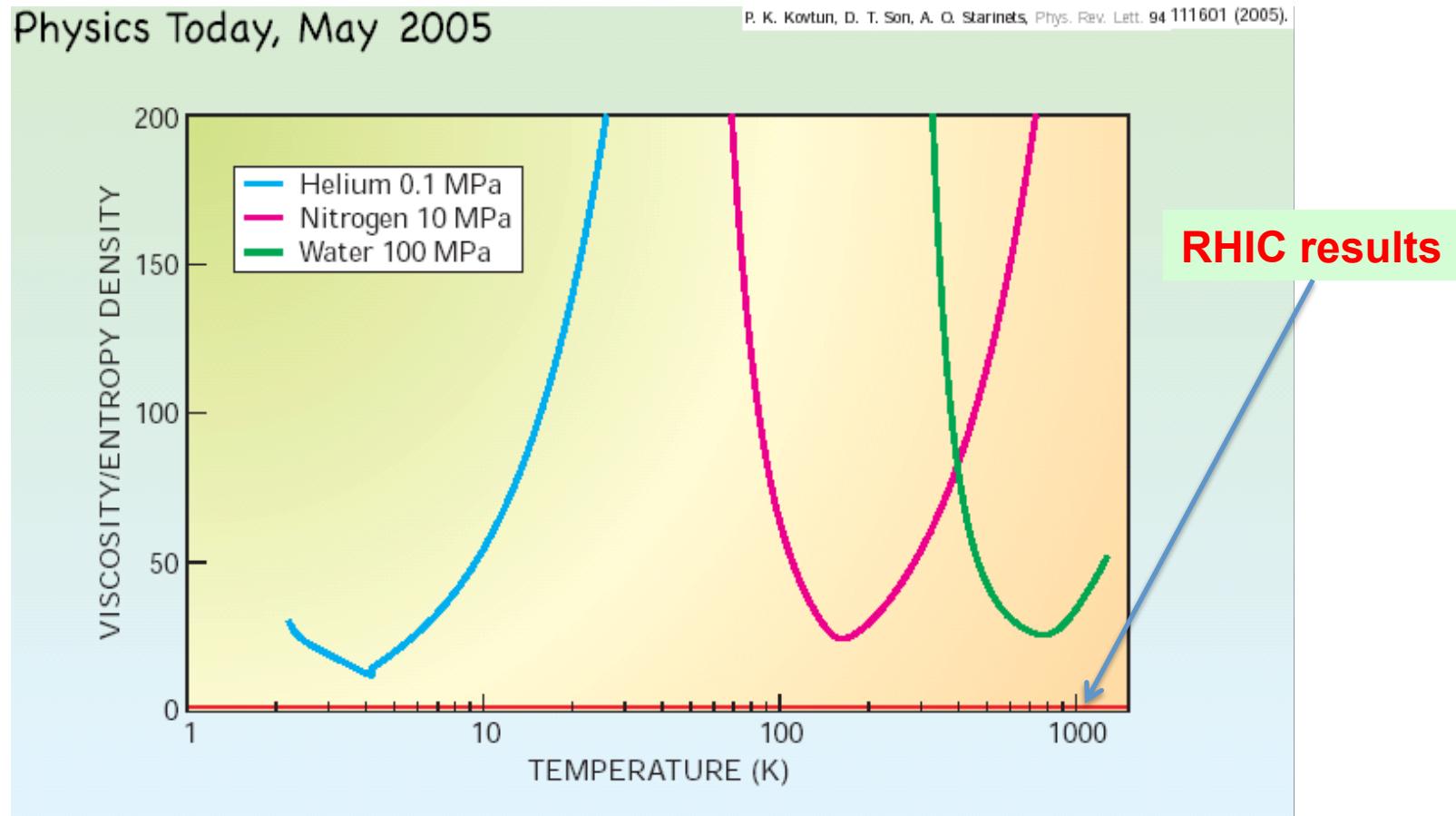
- Small value of specific viscosity over entropy η/s
- Model uncertainty dominated by initial eccentricity ε

Model: Song *et al.* arXiv:1011.2783

Low η/s QCD Matter Created at RHIC

Physics Today, May 2005

P. K. Kovtun, D. T. Son, A. O. Starinets, Phys. Rev. Lett. 94 111601 (2005).



Heavy Ion Collisions at RHIC: “Strongly Interaction Matter” with small $\eta/s \leq 1/4\pi$, *at the quantum limit.*

Antimatter Discoveries at RHIC

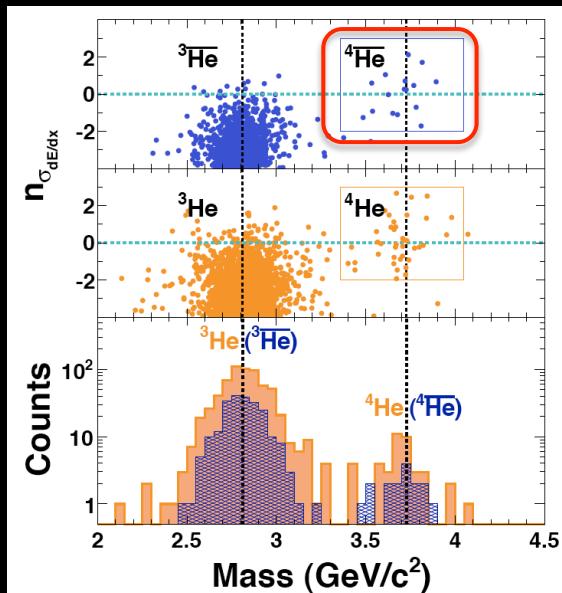
nature

April, 2011

“Observation of the Antimatter Helium-4 Nucleus”

by STAR Collaboration

Nature, 473, 353(2011).



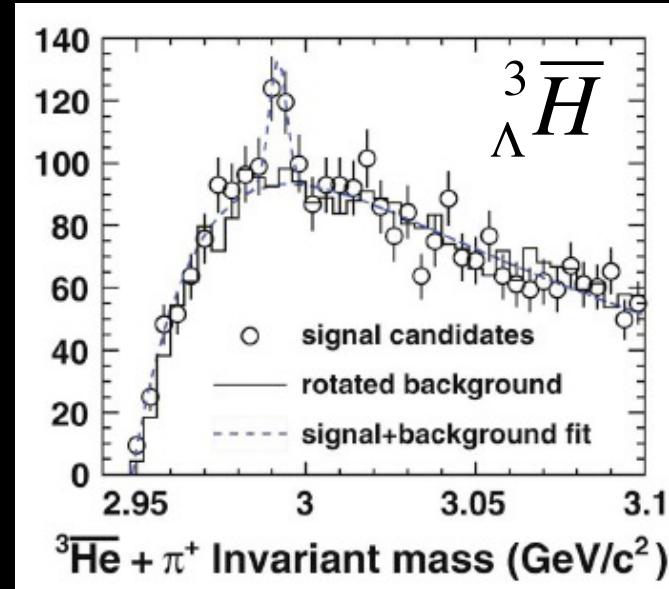
Science

March, 2010

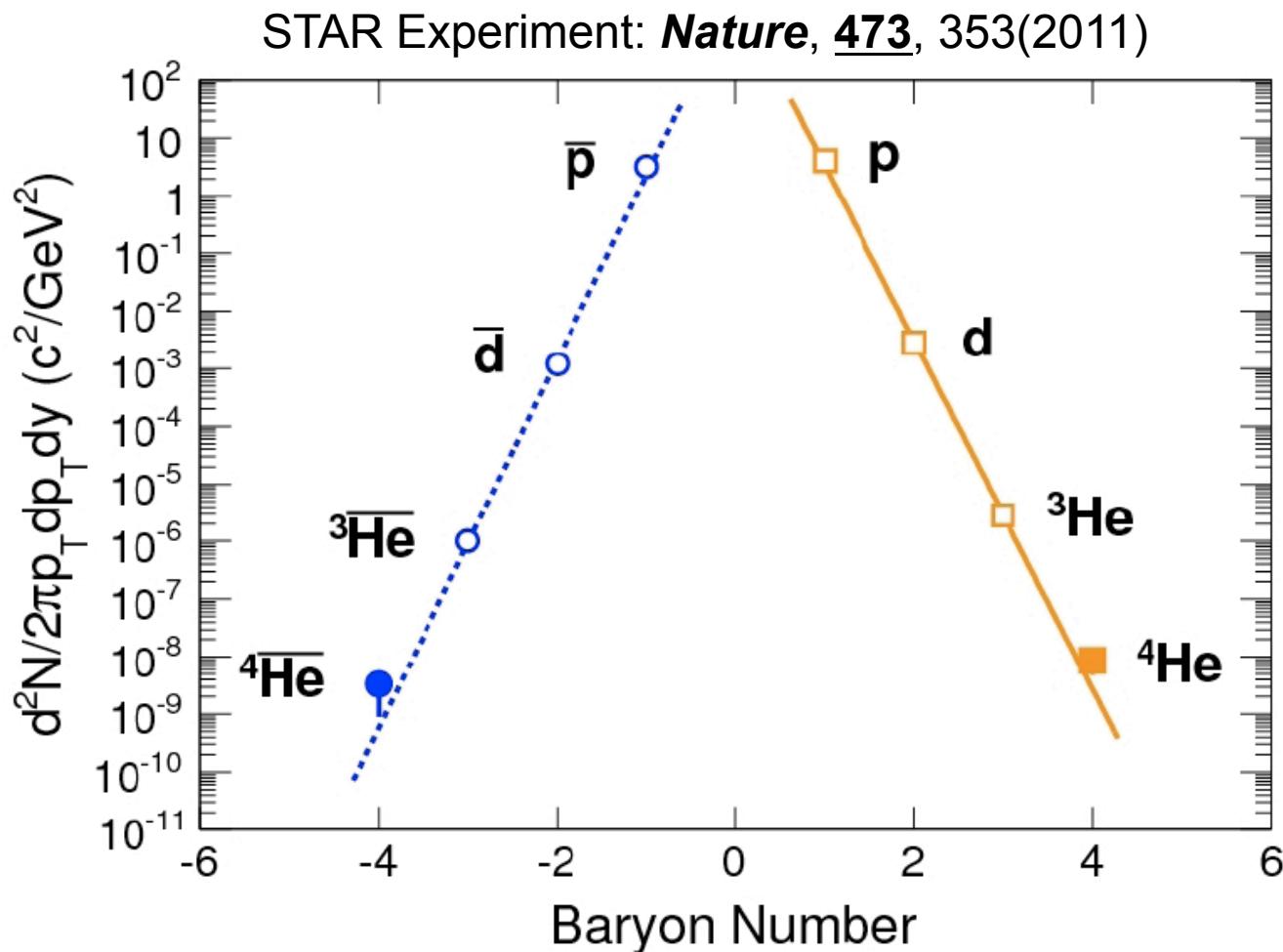
“Observation of an Antimatter Hypernucleus”

by STAR Collaboration

Science, 328, 58(2010).



Light Nuclei Productions at RHIC



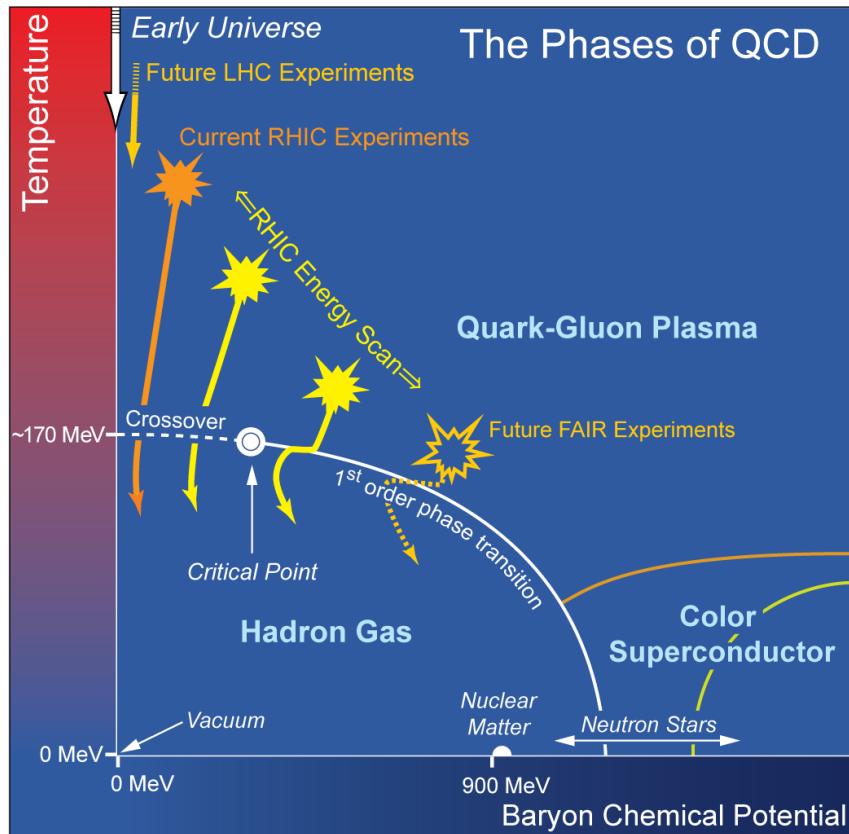
- 1) In high-energy nuclear collisions, $N(d) \gg N(\alpha)$:
QGP \rightarrow (anti)light nuclei via coalescence
- 2) In the Universe, $N(d) \ll N(\alpha)$: $N(\text{anti-}\alpha)$?

Summary I: sQGP formed at 200 GeV

- (1) In high-energy nuclear collisions, hot and dense ***matter***, with ***partonic degrees of freedom*** and ***collectivity***, has been formed
- (2) The matter behavior like a ***quantum liquid*** with small η/s
- (3) Partonic matter → antimatter: ${}^3_{\Lambda}\overline{H}$, ${}^4\overline{He}$

What is the structure of the QCD matter?

QCD Phase Structure and BES at RHIC



2010: 62.4, 39, 11.5, 7.7 GeV
2011: 19.6, 27 GeV

- LGT prediction on the transition temperature T_c is robust.

- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.

- Experimental evidence for either the critical point or 1st order transition is important for our knowledge of the QCD phase diagram*.

- M. Stephanov, K. Rajagopal, and E. Shuryak, *PRL* **81**, 4816(98); K. Rajagopal, *PR* **D61**, 105017 (00)

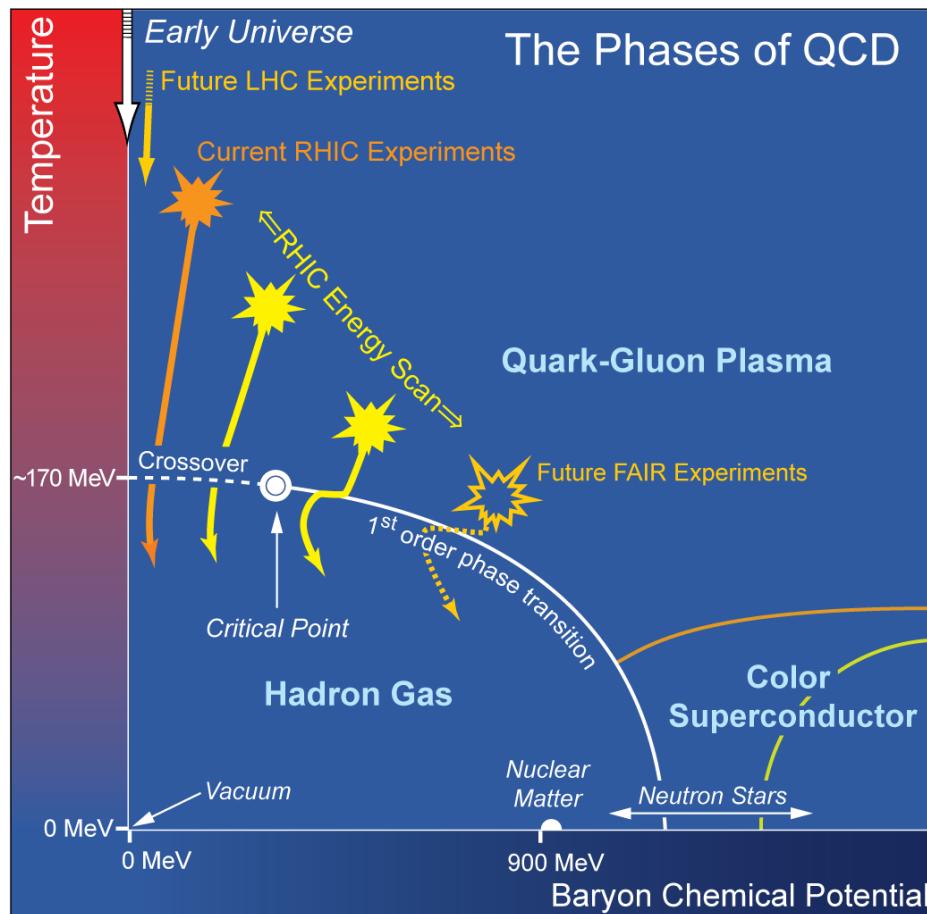
US NPLRP:

<http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf>

Beam Energy Scan at RHIC

Study QCD Phase Structure

- Signals of phase boundary
- Signals for critical point



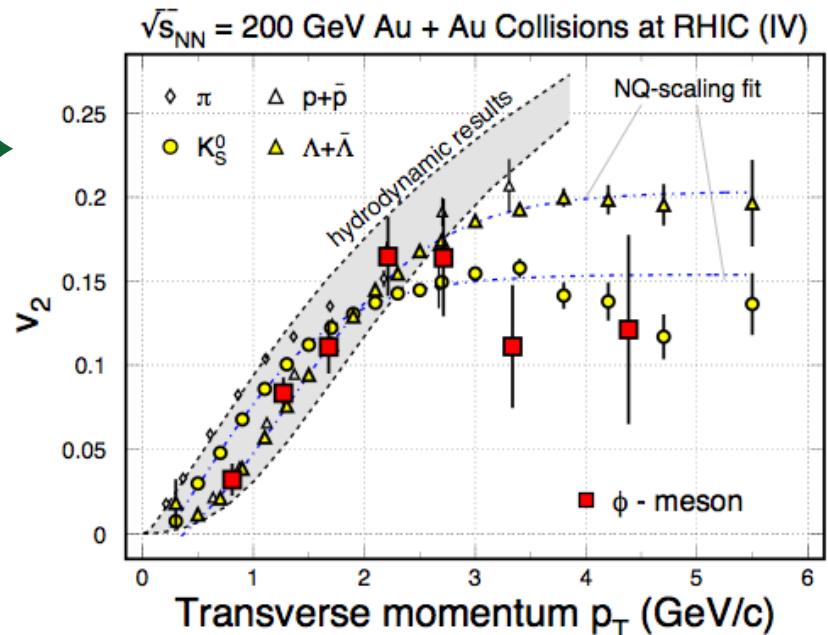
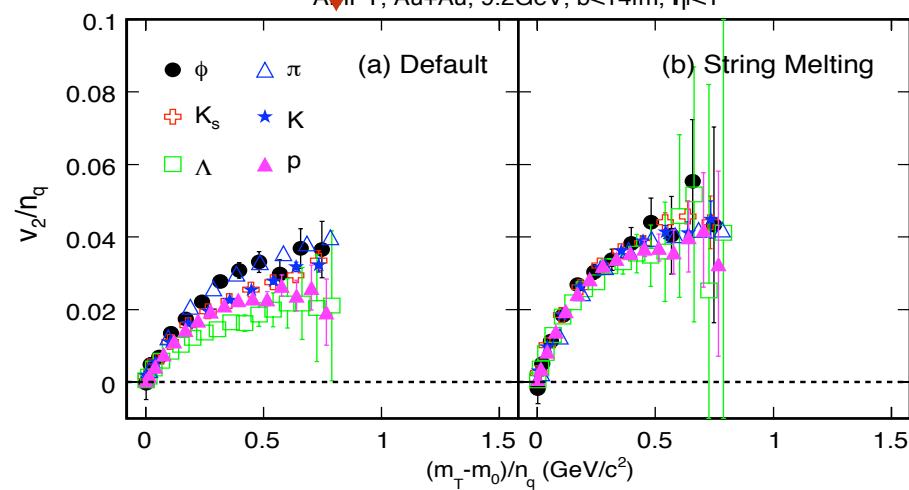
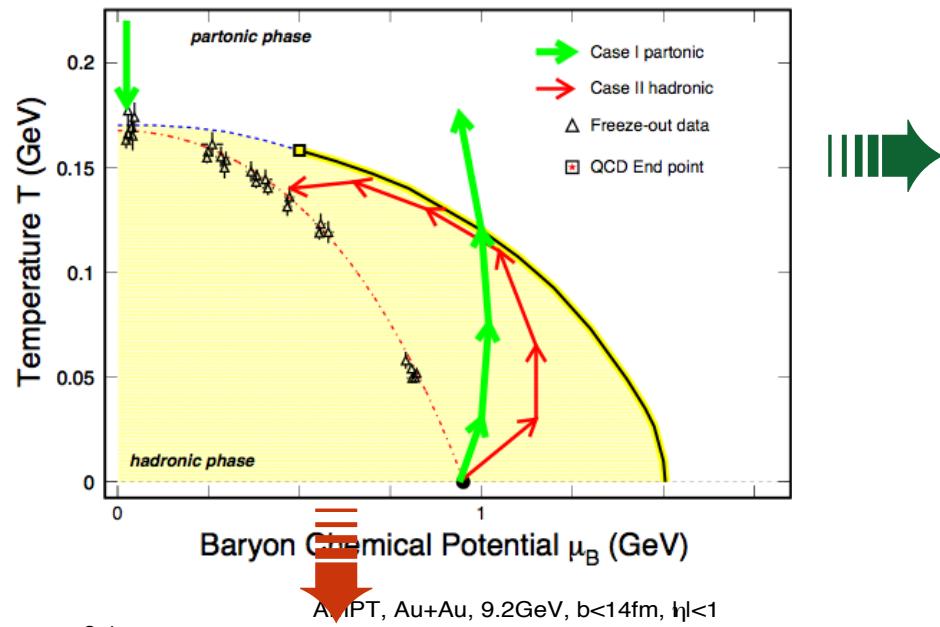
Observations:

- (1) v_2 - NCQ scaling:**
partonic vs. hadronic dof
- (2) Dynamical correlations:**
partonic vs. hadronic dof
- (3) Azimuthally HBT:**
1st order phase transition
- (4) Fluctuations:**
Critical point, correl. length
- (5) Directed flow v_1**
1st order phase transition

- <http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493>

- arXiv:1007.2613

Observable*: NCQ Scaling in v_2



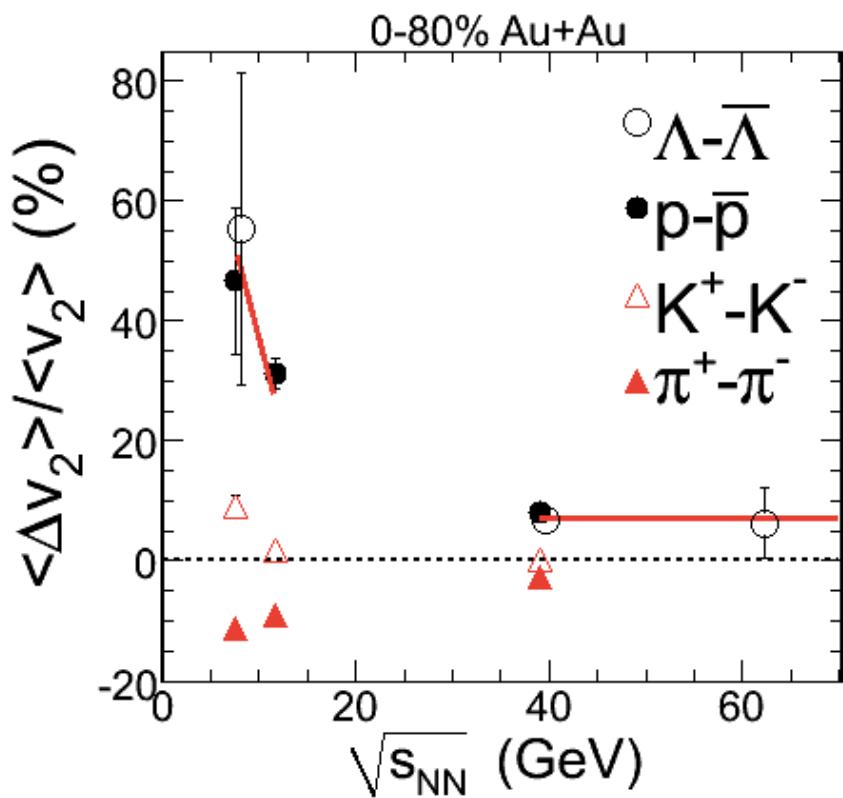
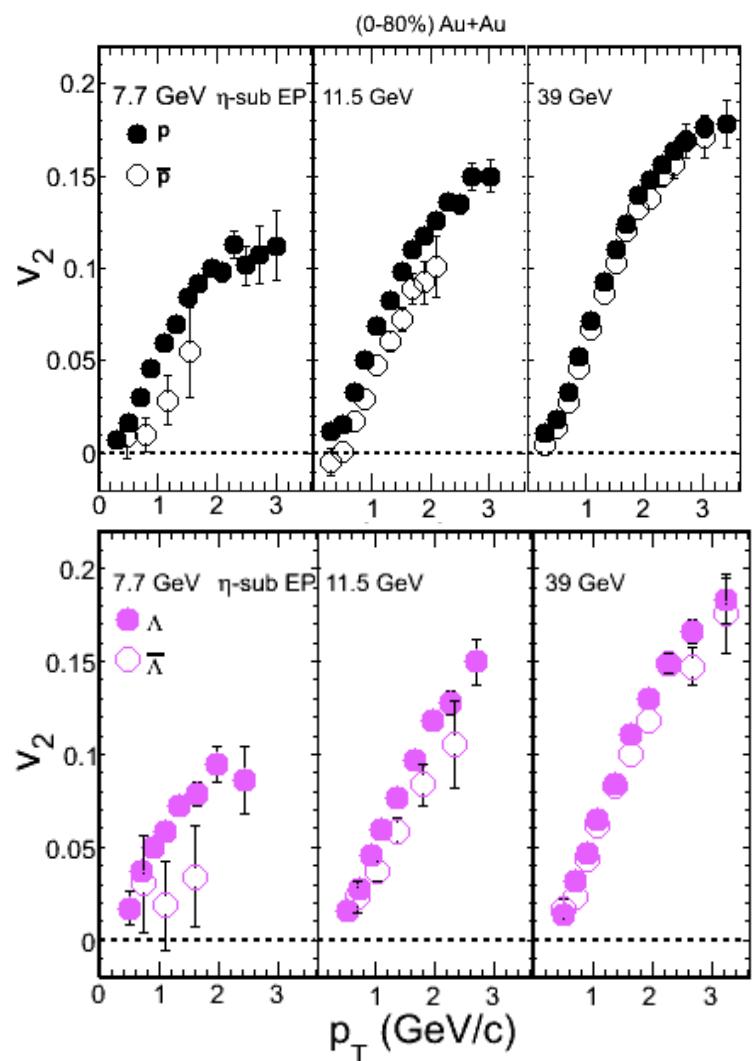
- $m_\phi \sim m_p \sim 1$ GeV
- $s\bar{s} \Rightarrow \phi$ not $K^+K^- \Rightarrow \phi$
- $\sigma_{\phi h} \ll \sigma_{p\pi, \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of ϕ will be small.

* Thermalization is assumed!

STAR Collaboration: F. Liu, S.S. Shi, K.J. Wu et al.

Particle and Anti-Particle v_2 vs. $\sqrt{s_{NN}}$



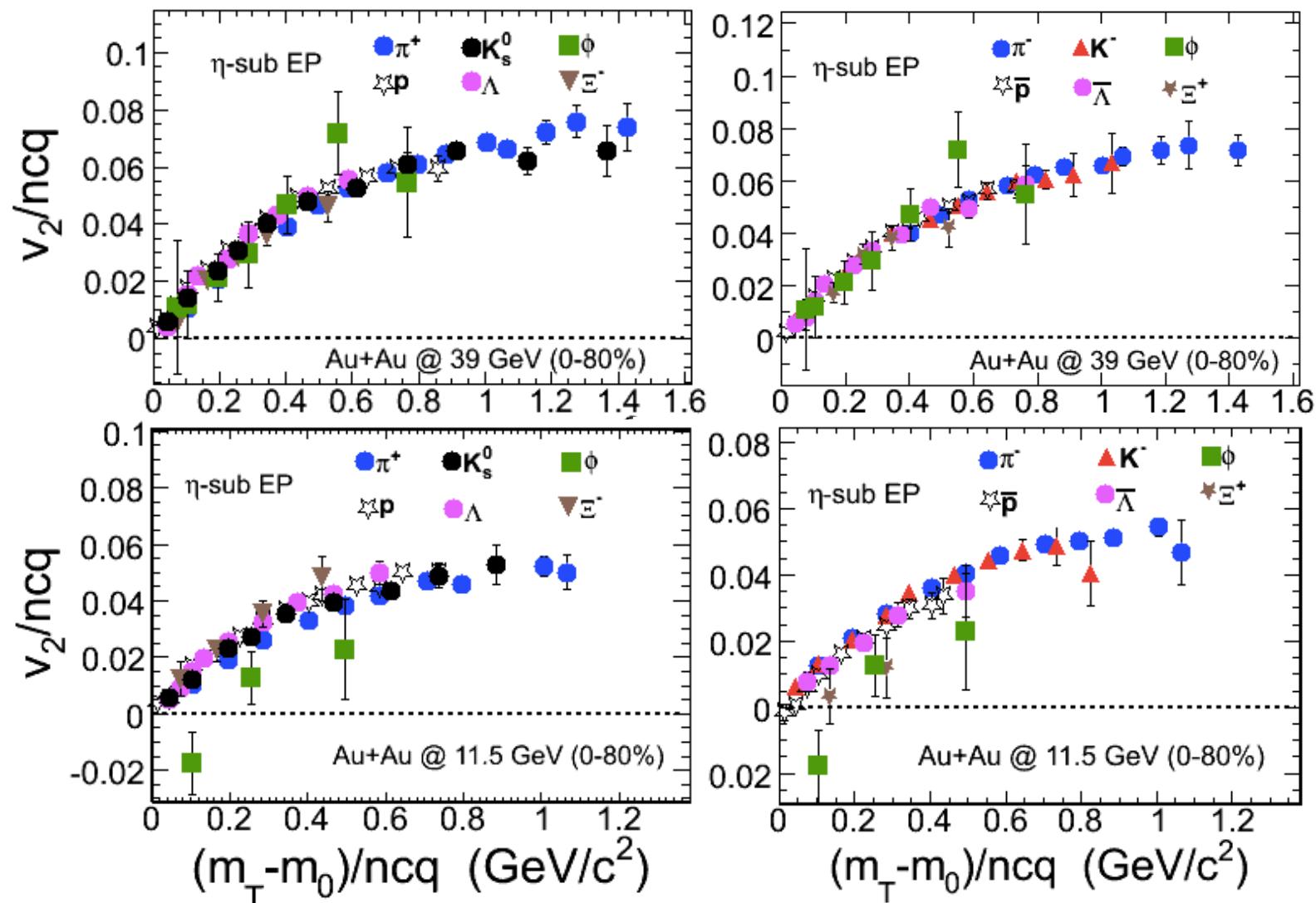
At $\sqrt{s_{NN}} \leq 11.5 \text{ GeV}$:

- $v_2(\text{baryon}) > v_2(\text{anti-baryon})$
- $v_2(\pi^+) < v_2(\pi^-)$
- $v_2(K^-) < v_2(K^+)$

STAR: Quark Matter 2011

Hadronic interactions are dominant

ϕ -meson v_2



The ϕ v_2 falls off trend from other hadrons at 11.5 GeV

Summary II: NCQ-Scaling in v_2

- 1) Partonic collectivity in 200 GeV collisions
- 2) At $\sqrt{s_{NN}} \leq 11.5$ GeV
 - $v_2(\text{baryon}) > v_2(\text{anti-baryon})$
 - $v_2(\phi) < v_2(\text{hadron})$

→ v_2 -NCQ-scaling broken
→ [hadronic] $\otimes \sqrt{s_{NN}} \leq 11.5$ GeV
[partonic] $\otimes \sqrt{s_{NN}} \geq 39$ GeV

Where is the critical point?

Susceptibilities and Moments

Thermodynamic function:

$$\frac{p}{T^4} = \frac{1}{\pi^2} \sum_i d_i (m_i/T)^2 K_2(m_i/T) \cosh[(B_i \mu_B + S_i \mu_S + Q_i \mu_Q)/T]$$

The susceptibility: $T^{n-4} \chi_q^{(n)} = \frac{1}{T^4} \frac{\partial^n}{\partial(\mu_q/T)^n} P\left(\frac{T}{T_c}, \frac{\mu_q}{T}\right) \Big|_{T=T_c}, \quad q = B, Q, S$

$$\chi_q^{(1)} = \frac{1}{VT^3} \langle \delta N_q \rangle$$

$$\chi_q^{(2)} = \frac{1}{VT^3} \langle (\delta N_q)^2 \rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3} \langle (\delta N_q)^3 \rangle$$

$$\chi_q^{(4)} = \frac{1}{VT^3} \left(\langle (\delta N_q)^4 \rangle - 3 \langle (\delta N_q)^2 \rangle^2 \right)$$

$$\begin{aligned} \frac{T^2 \chi_q^{(4)}}{\chi_q^{(2)}} &= \kappa \sigma^2 \\ \frac{T \chi_q^{(3)}}{\chi_q^{(2)}} &= S \sigma \end{aligned}$$

Conserved
Quantum
Number

Thermodynamic function \Leftrightarrow Susceptibility \Leftrightarrow Moments
Model calculations, e.g. LGT, HRG \Leftrightarrow Measurements

Non-Gaussian Fluctuations

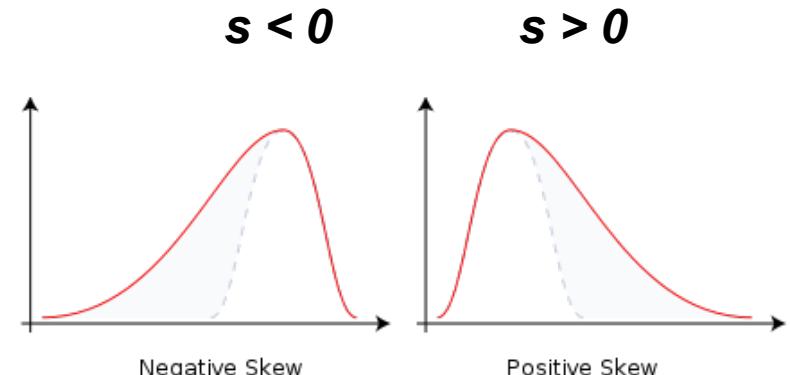
N : event by event multiplicity distribution

$$m = \langle N \rangle$$

$$s = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$$

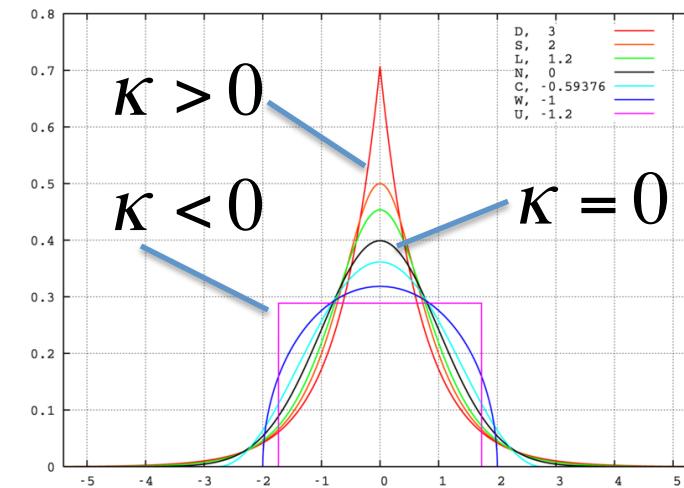
$$\sigma = \sqrt{\langle (N - \langle N \rangle)^2 \rangle}$$

$$\kappa = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$$

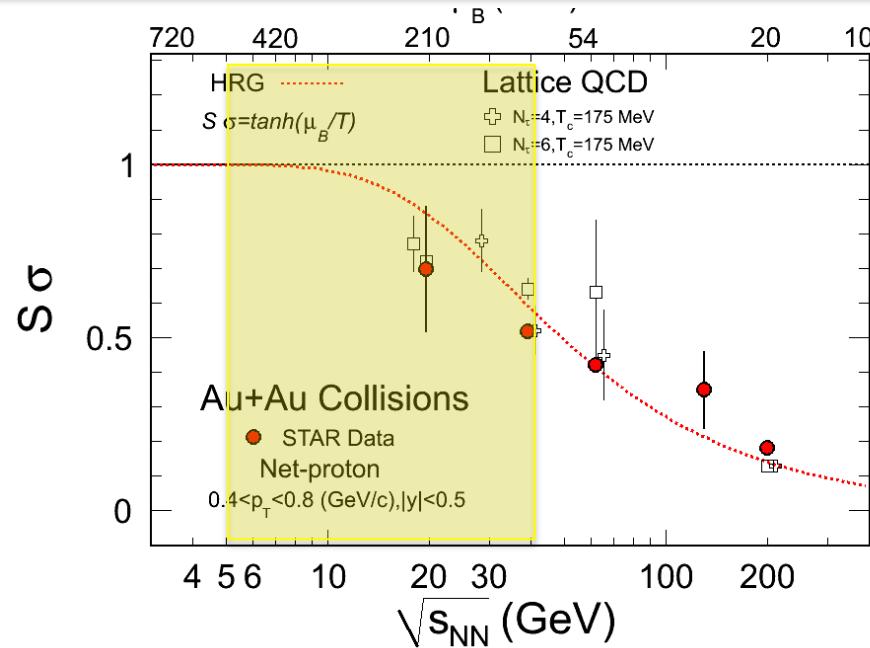
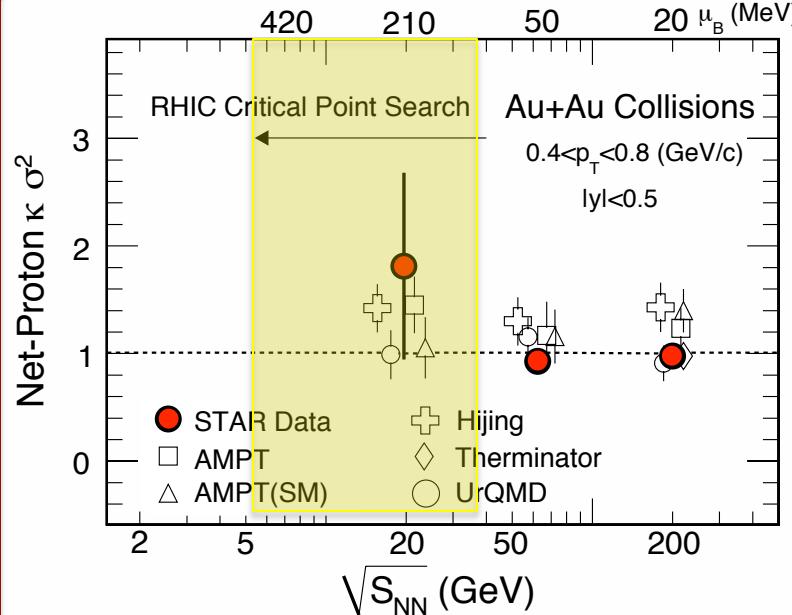


For a Gaussian distribution, the $s=0$, $\kappa=0$. **Ideal probe of the non-Gaussian fluctuations at critical point.**

Higher order correlations are correspond to higher power of the correlation length of the system: **more sensitive to critical phenomena.**
Price: large number of events required.



High Moments: Critical Point Search



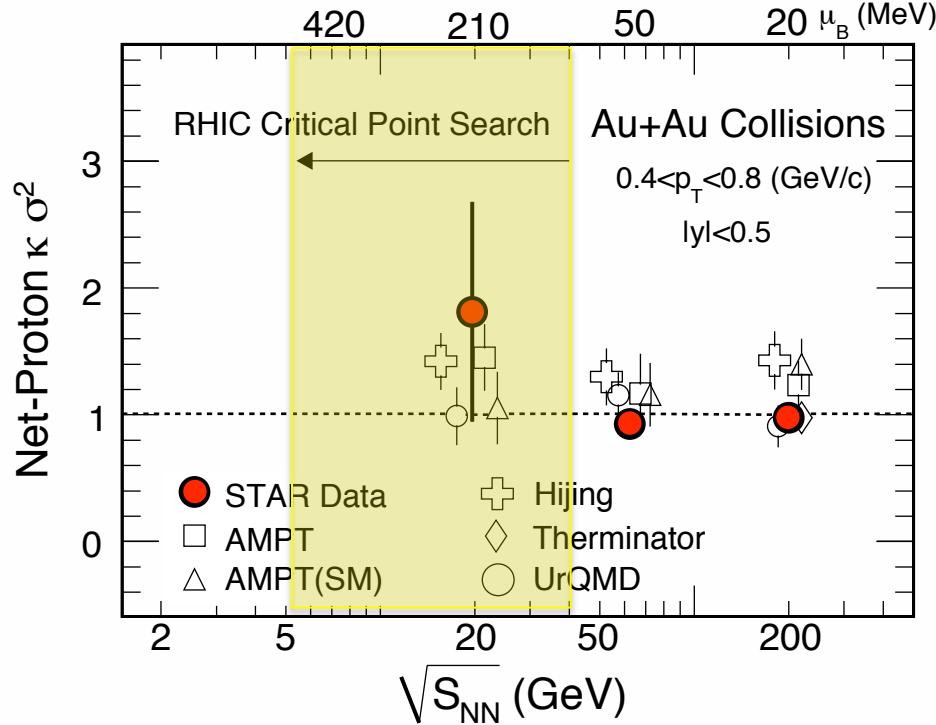
- Measure conserved quantities, B , s , and Q .
- First: High order fluctuation results consistent with thermalization.
- First: Tests the *long distance QCD* predictions in hot/dense medium.

Caveats: (a) static vs. dynamic; (b) net-B vs. net-p; (c) potential effects of freeze-out...

- R. Gavai, S. Gupta, 1001.3796 / F. Karsch, K. Redlich, 1007.2581 / M. Stephanov, 0911.1772.
- STAR: PRL105, 02232(2010) and references therein.

Remarks

STAR: *PRL*, **105**, 22302(2010)



Energy Scan in Au+Au collisions:

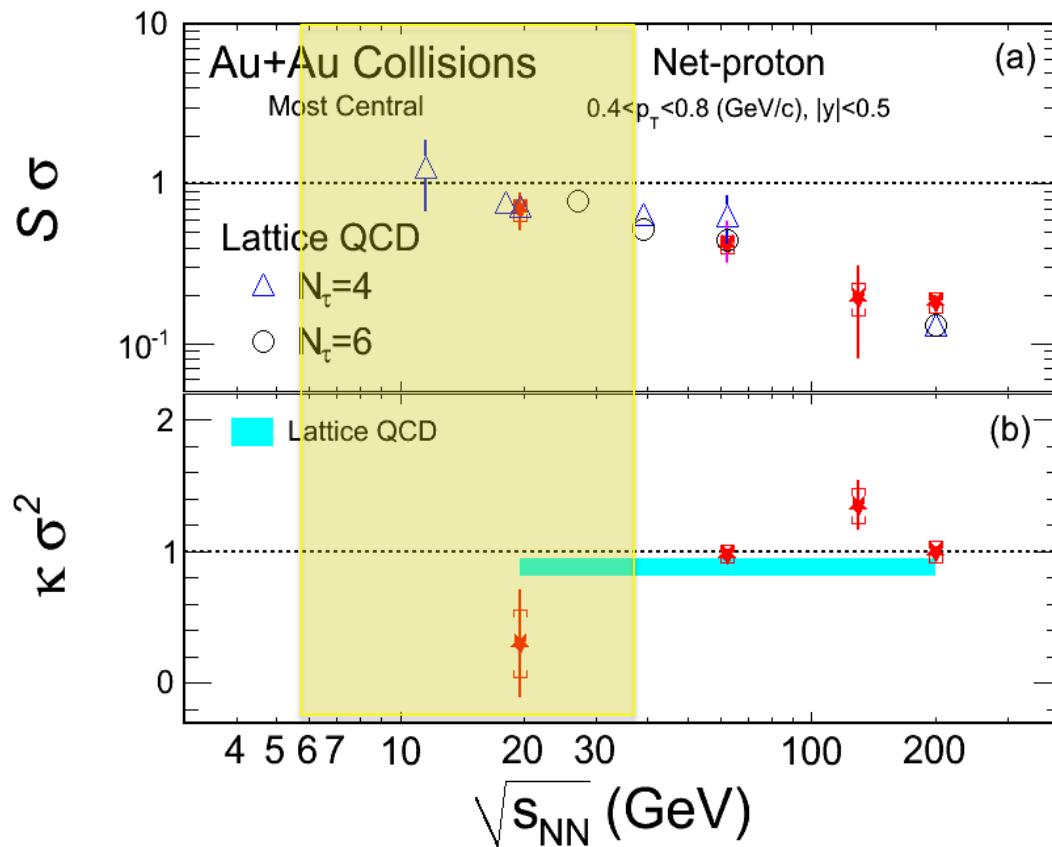
Run 10: 7.7, 11.5, 39 GeV

Run 11: 19.6, 27 GeV

- 1) Centrality averaged events. In this analysis, effects of volume and detecting efficiencies are all canceled out.
- 2) ALL transport model results values are higher than unity, except the Theminator result at 200GeV. LGT predicted values around 0.8-0.9, due to finite chemical potential effect.
- 3) Test of thermalization with higher moments.
- 4) **Critical point effect:** non-monotonic dependence on collision energy.

- STAR: PRL105, 22302(2010).
- F. Karsch and K. Redlich, arXiv:1007.2581

Comparing with LGT Results



References:

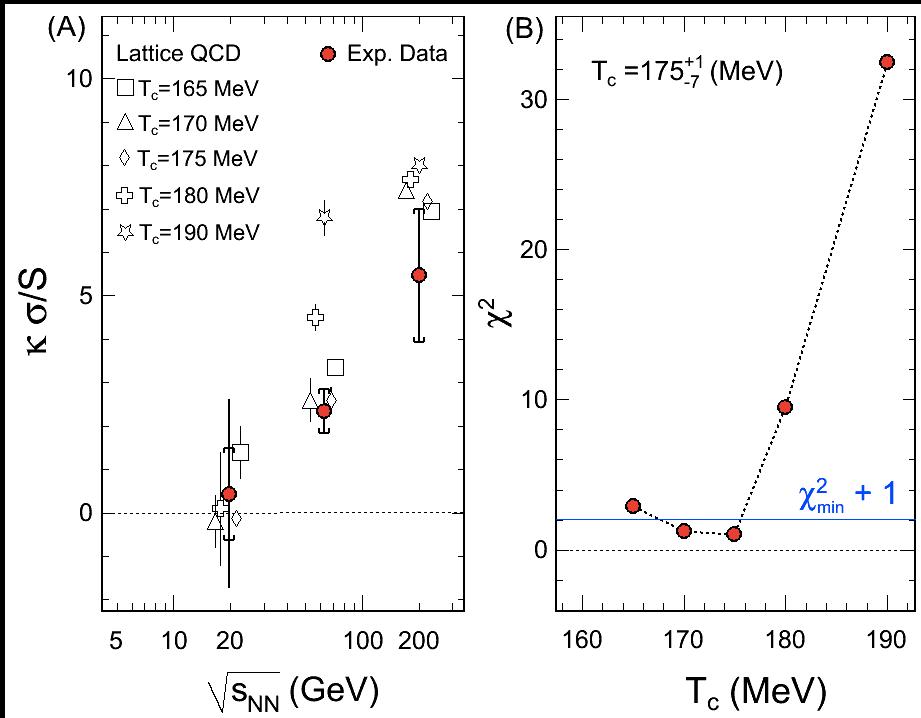
- STAR, *PRL*105, 22303(10)
- F. Karsch and K. Redlich, *PLB*695, 136(11)
- R.V. Gavai and S. Gupta: *PLB*696, 459(11)

Assumptions:

- (a) Freeze-out temperature is close to LGT T_c
- (b) Thermal equilibrium reached in central collisions
- (c) Taylor expansions, at $\mu_B \neq 0$, on LGT results are valid

→ Lattice results are consistent with data for $60 < \sqrt{s_{NN}} < 200 \text{ GeV}$

Scale of Hot/Dense Matter on LGT



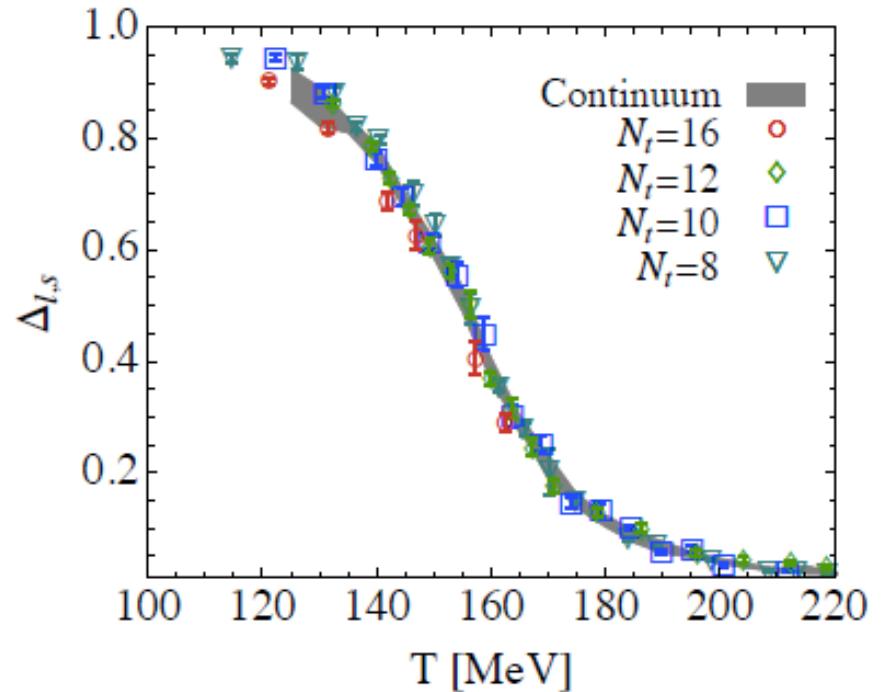
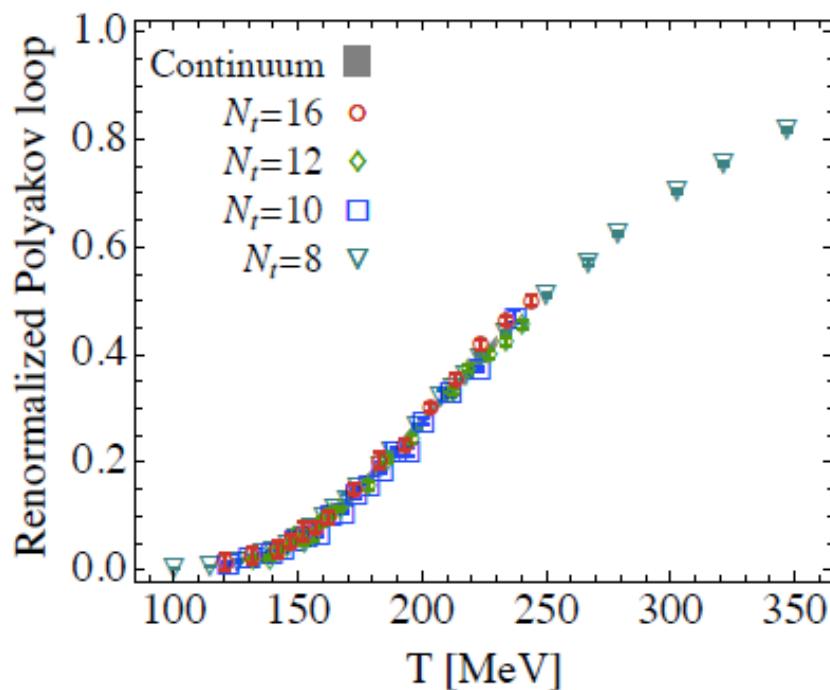
“Scale for the Phase Diagram of Quantum Chromodynamics”

Science, 332, 1525(2011)

- 1) Central collisions at RHIC, the high moments measurements are consistent with thermal equilibrium assumption
- 2) Scale of LGT, determined with the data, is: $T_c = 175^{+1}_{-7}$ (MeV)

STAR, *PRL* 105, 22303(2010); S. Gupta, X.F. Luo, B. Mohanty, H.G. Ritter, NX, *Science*, 332, 1525(2011); F. Karsch and K. Redlich, *PLB* 695, 136(2011); R.V. Gavai and S. Gupta, *PLB* 696, 459(2011).

Lattice: Phase Transition Temperature



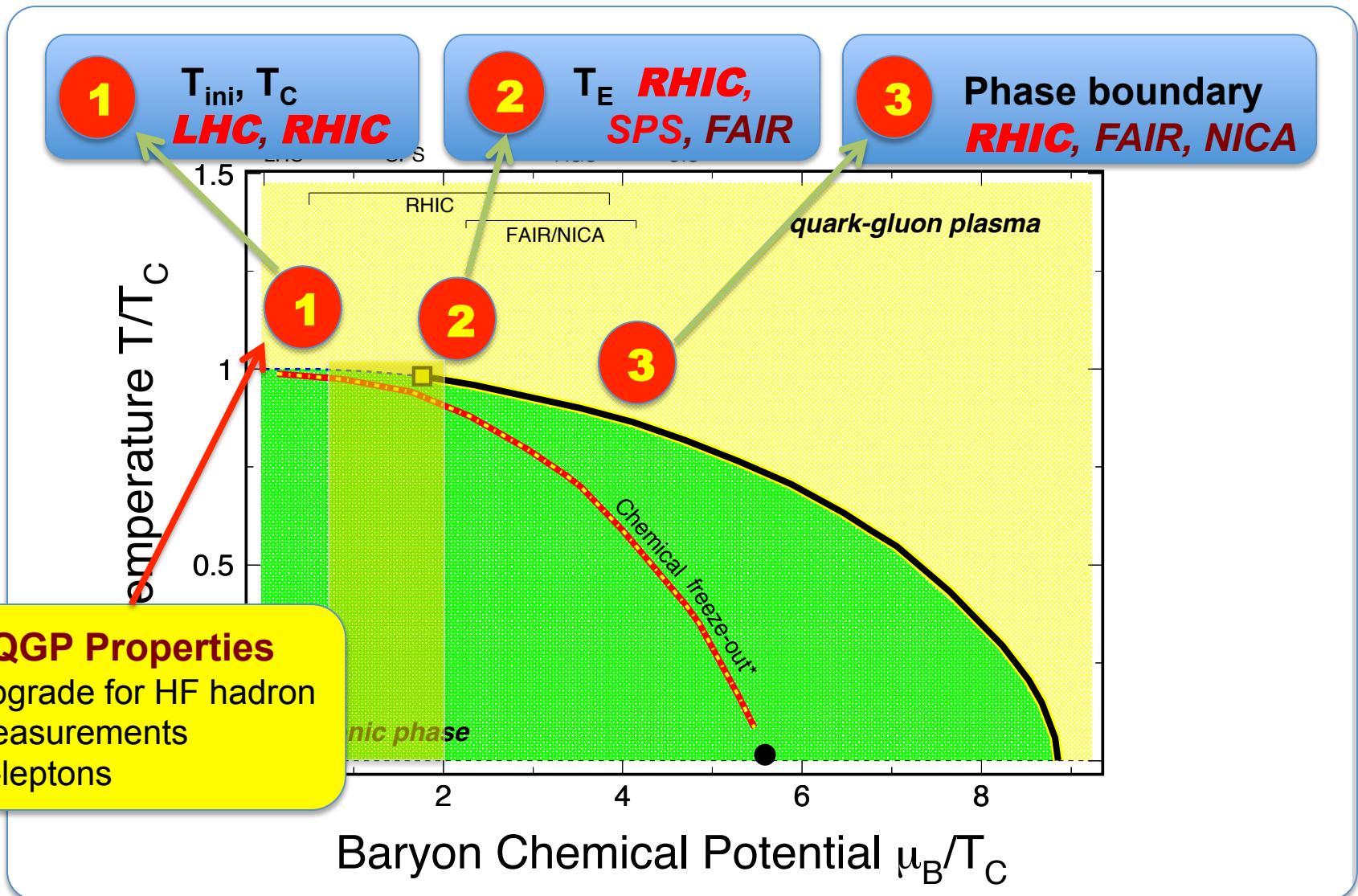
Action	Temperature
Polyakov Loop	$T_c^{\text{conf}} \sim 170 \text{ MeV}$
Chiral Operator	$T_c^{\text{chiral}} \sim 160 \text{ MeV}$
RHIC Data	$T_c^{\text{Exp}} \sim 175^{+1}_{-7} \text{ MeV}$

Summary

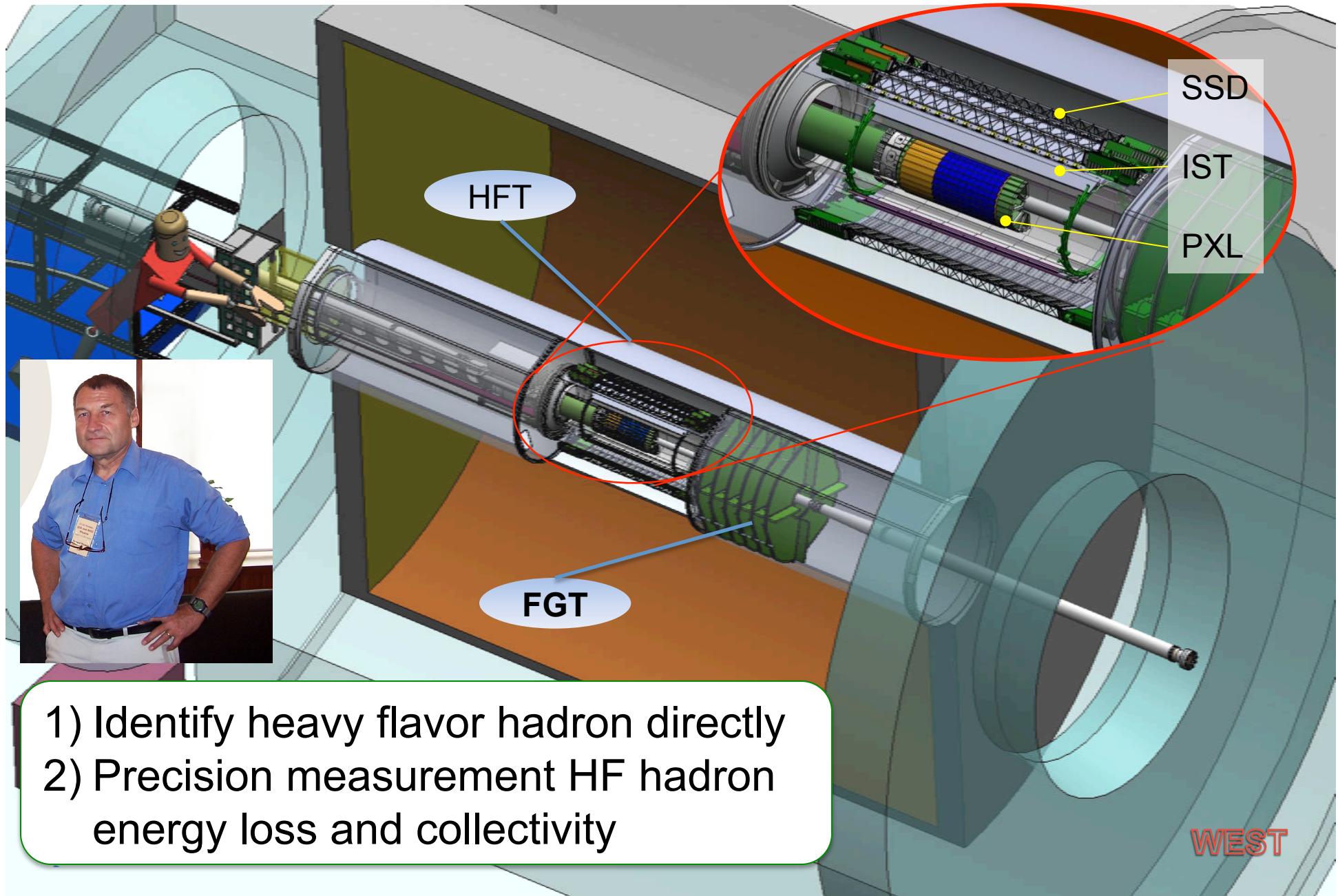
- (1) In high-energy nuclear collisions, hot and dense ***matter, with partonic degrees of freedom and collectivity, has been formed***
- (2) The matter behavior like a ***quantum liquid with*** small η/s
- (3) Partonic matter → antimatter: ${}^3_{\Lambda}\overline{H}$, ${}^4\overline{He}$
- (4) **[partonic] < $\mu_B \sim 110\text{--}320$ (MeV) < [hadronic]**
- (5) Net-proton distributions are consistent with LGT results. QCD Scale: $T_c=175^{+1}_{-7}$ (MeV)

Outlook:

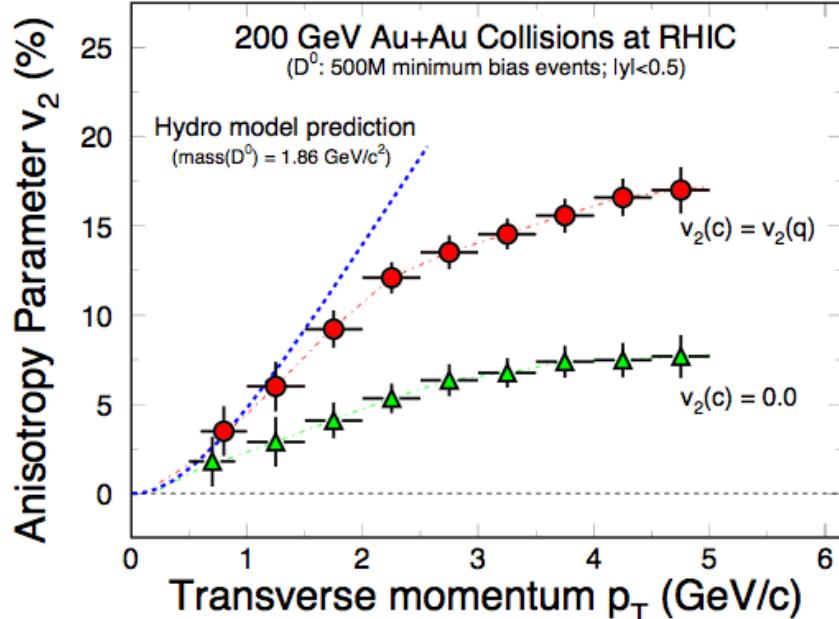
(7.7, 11.5, 15.5, 19.6, 27, 39, 62, 200 GeV)



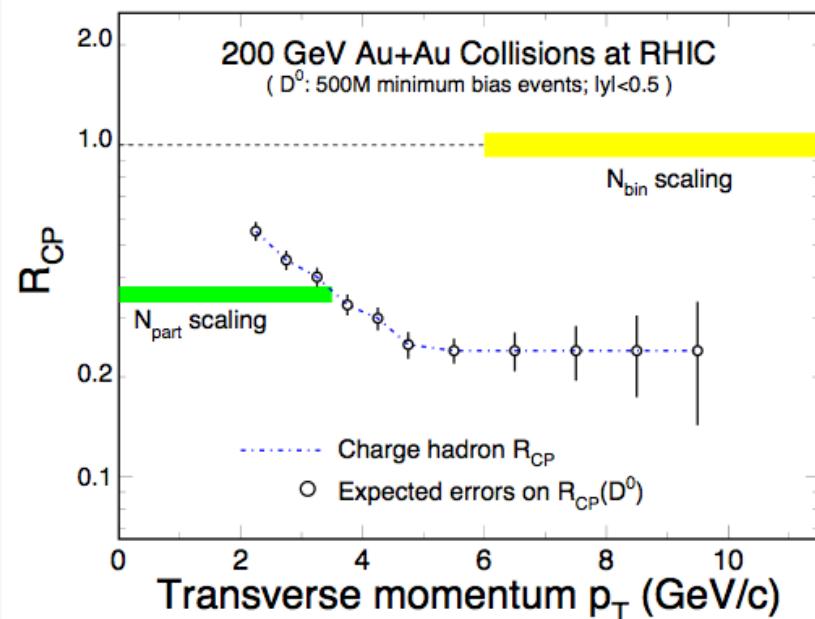
Outlook: Heavy Flavor Tracker (HFT) at STAR



HFT: Charm Hadron v_2 and R_{AA}



- 200 GeV Au+Au m.b. collisions (500M events).
- Charm hadron collectivity \Rightarrow drag/diffusion constants \Rightarrow
- Medium properties!**
- Light quark thermalization!**



- 200 GeV Au+Au m.b. collisions ($|y|<0.5$ 500M events)
- Charm hadron $R_{AA} \Rightarrow$
- Energy loss mechanism!**
- QCD in dense medium!**

Physics of the Heavy Flavor Tracker at STAR

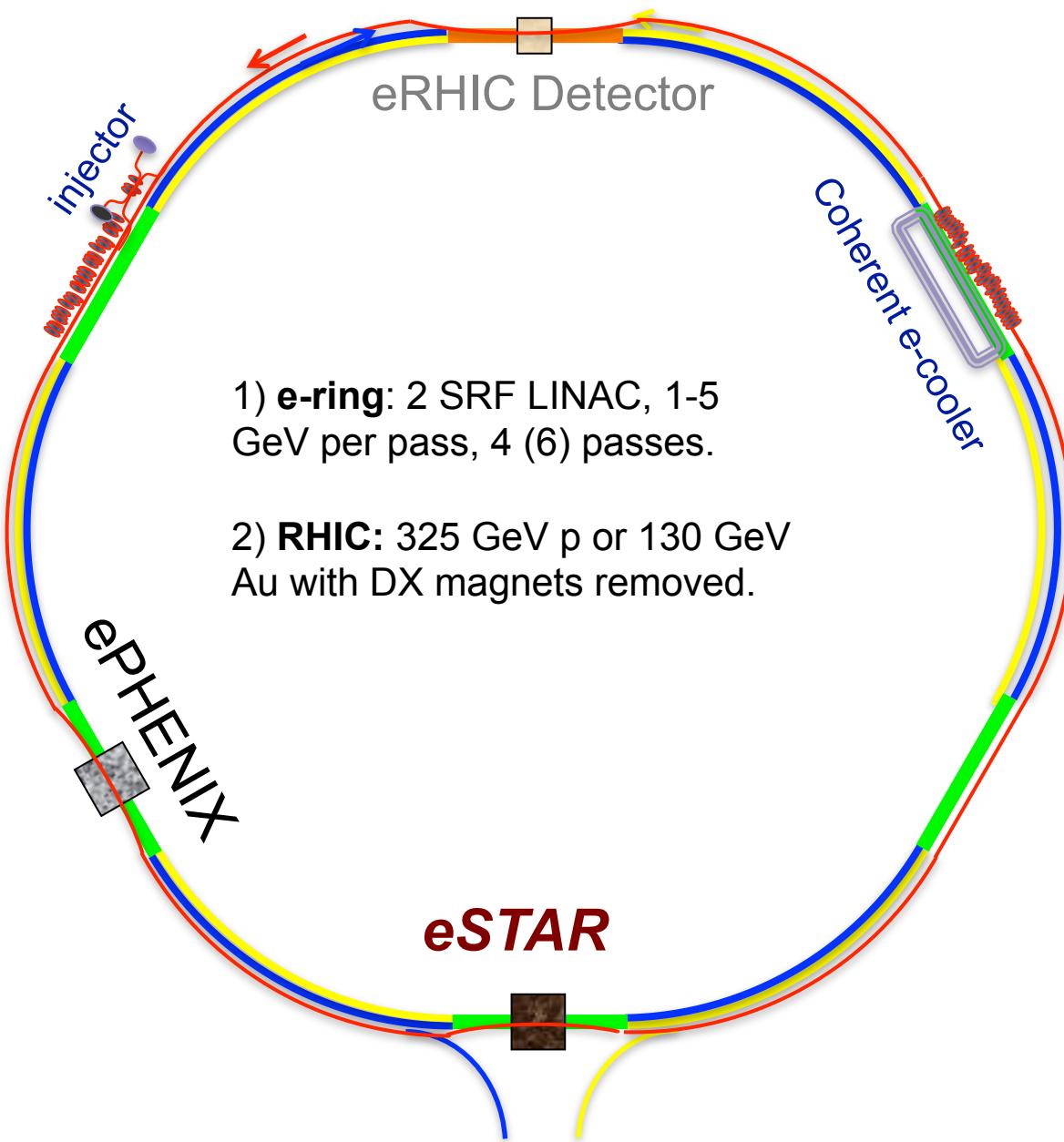
1) Direct HF hadron measurements (p+p and Au+Au)

- (1) Heavy-quark cross sections: $D^{0,\pm,*}$, D_S , Λ_C , B ...
- (2) Both spectra (R_{AA} , R_{CP}) and v_2 in a wide p_T region: 0.5 - 10 GeV/c
- (3) Charm hadron correlation functions, heavy flavor jets
- (4) Full spectrum of the heavy quark hadron decay electrons

2) Physics

- (1) Measure heavy-quark hadron v_2 , heavy-quark collectivity, to study the medium properties **e.g. *light-quark thermalization***
- (2) Measure heavy-quark energy loss to study pQCD in hot/dense medium
e.g. *energy loss mechanism*
- (3) Measure di-leptons to study the ***direct radiation*** from the hot/dense medium
- (4) Analyze ***hadro-chemistry including heavy flavors***

Outlook: eRHIC



eRHIC:
(2022-2025)

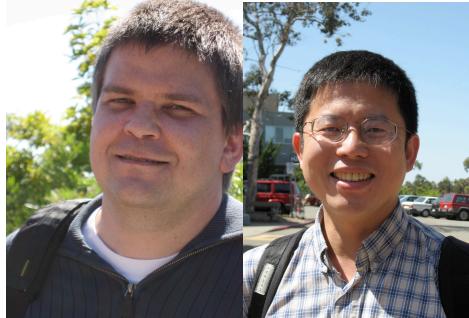
e beam: 20-30 GeV
p beam: 325 GeV
ion beam: 130 GeV
1 dedicated detector

ePHENIX/eSTAR:
(2018-2022)

e beam: 5 GeV
p beam: 325 GeV
ion beam: 130 GeV

S. Vigdor: 2010 RHIC operational review

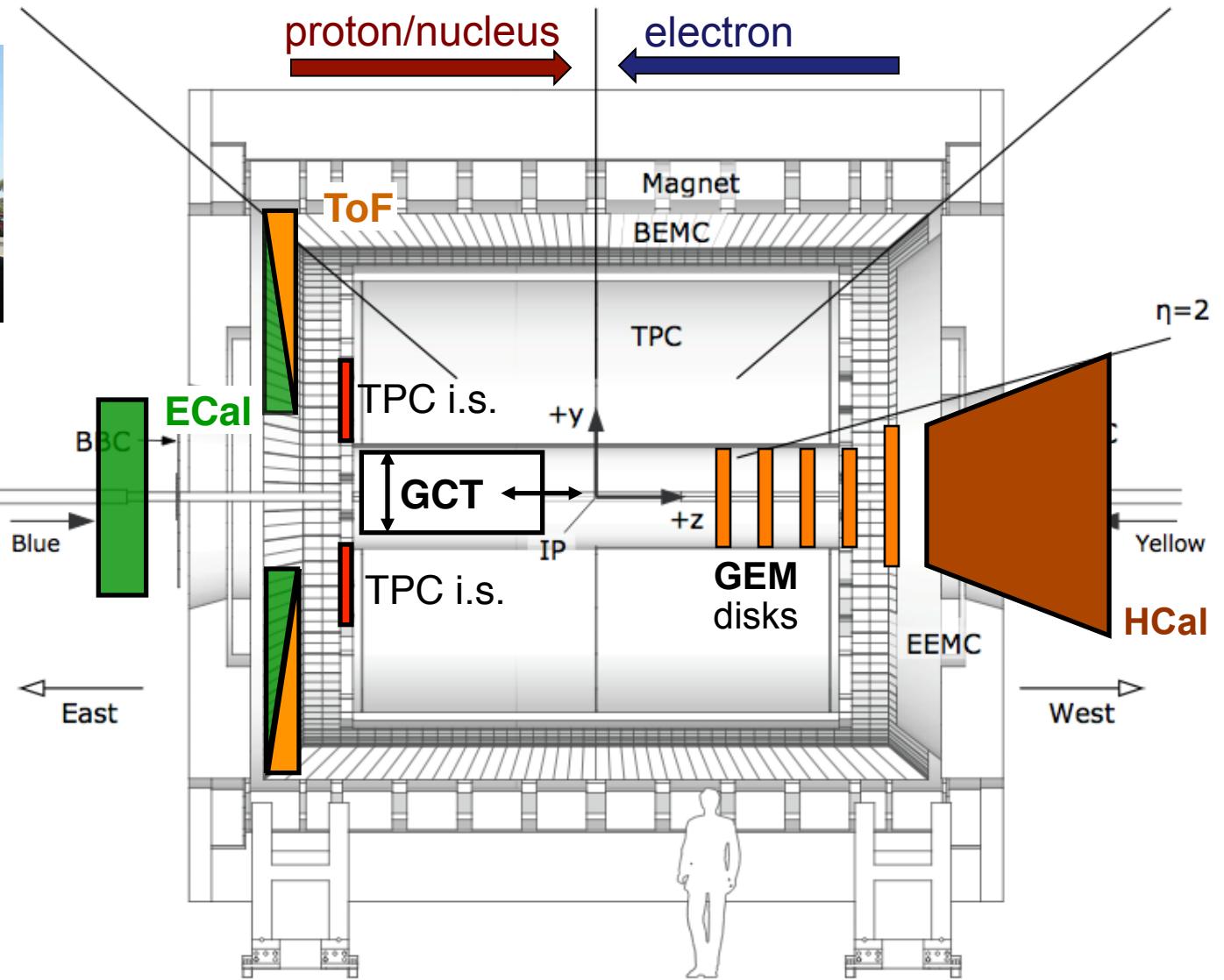
Outlook: from STAR into eSTAR



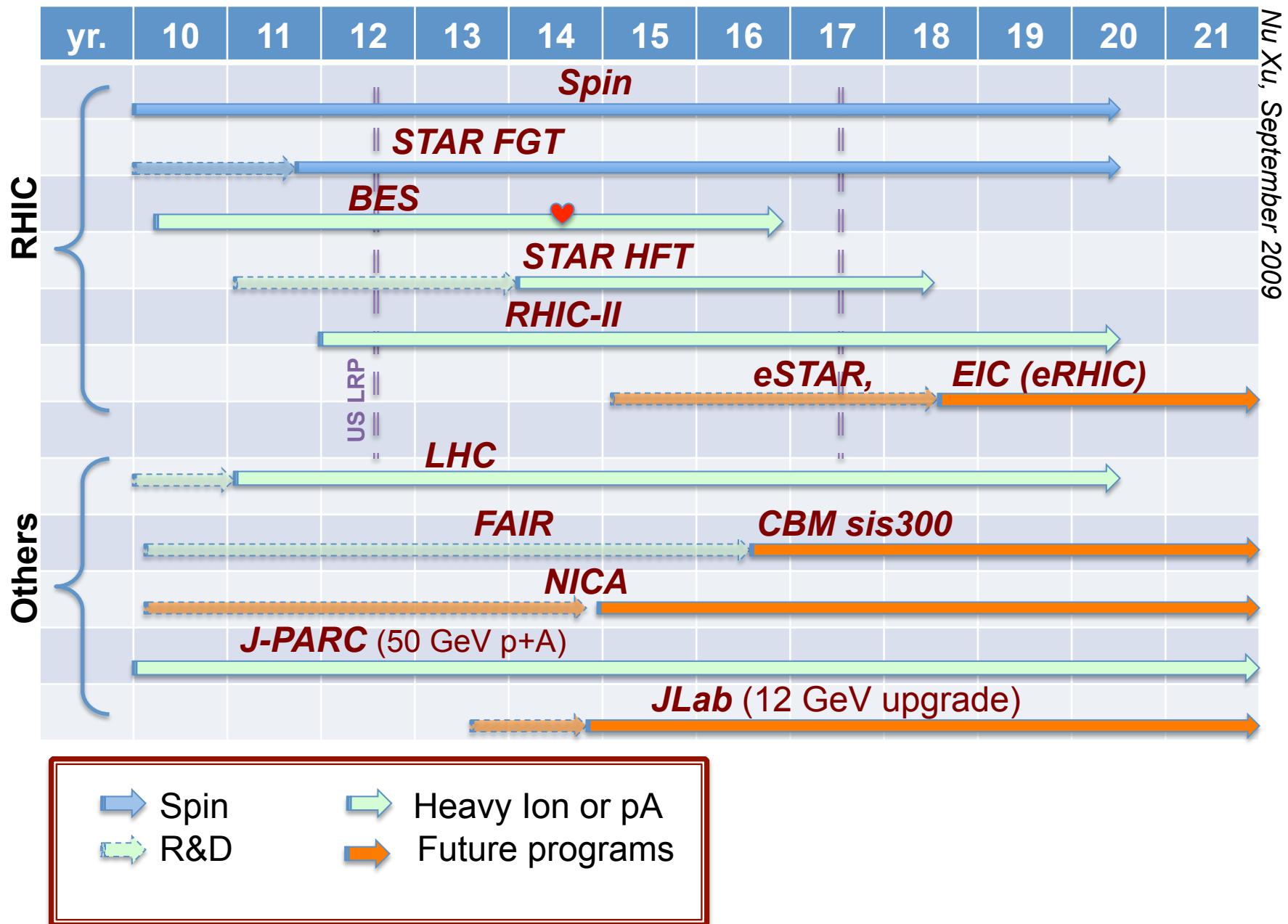
eSTAR Task Force:

- Ernst Sichtermann
- Zhangbu Xu (BNL)

- Detector R&D
- Science cases



Timeline of QCD and Heavy Ion Facilities



Summary

1) RHIC top Energy:

Properties of the QGP: T_i , T_c , η ...

2) RHIC Beam Energy Scan:

QCD critical point, phase boundary

3) Polarized p+p Collisions:

Sea quark and gluon contributions to proton helicity structure

4) Future: Evolution to small-x physics: eRHIC

- Partonic structures of nucleon and nuclei

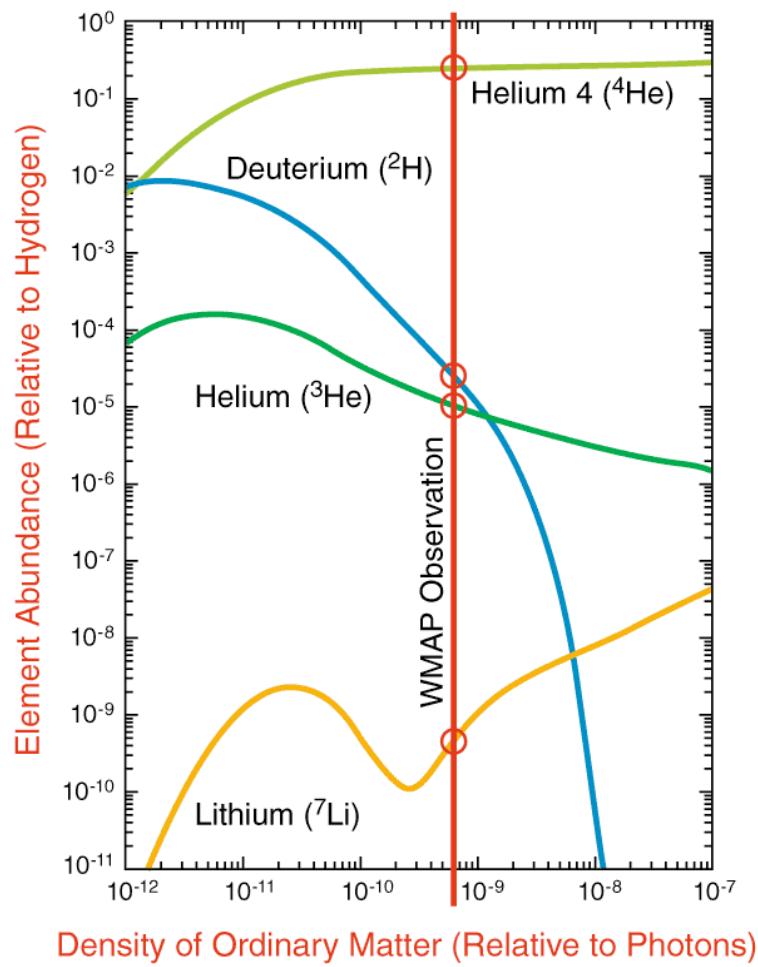
- Dynamical evolution from cold nuclear matter to hot QGP

Phase Structures of QCD Matter

*Many Thanks to the
Organizers!*

Nu Xu

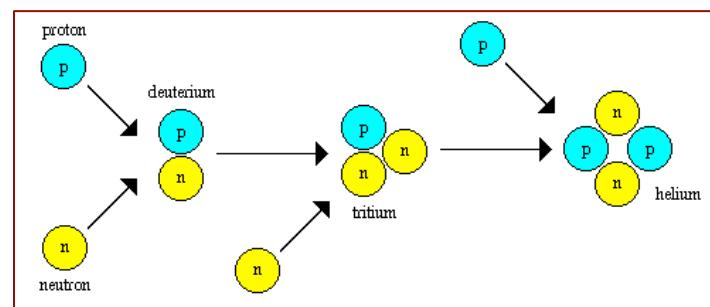
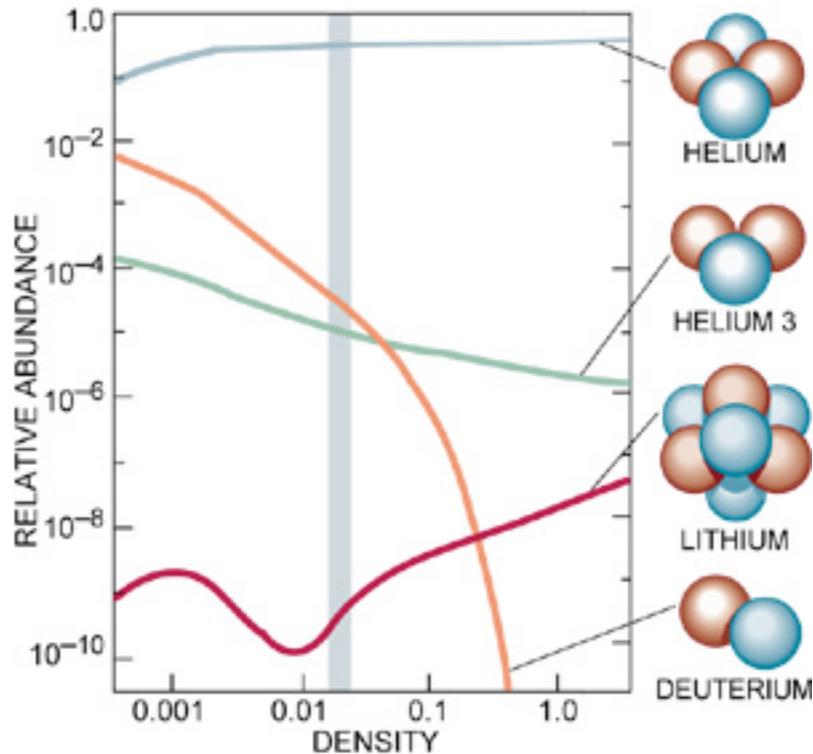
Atomic Nuclei Formation



NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

$$\frac{n_B}{n_\gamma} \approx 10^{-9}$$



Correlations, Susceptibilities, Moments

$$\delta N = N - \langle N \rangle$$

$$\langle (\delta N)^2 \rangle \approx \xi^2, \quad \langle (\delta N)^3 \rangle \approx \xi^{4.5}$$

$$\langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 \approx \xi^7$$

M. A. Stephanov, PRL. 102, 032301 (09)

$$S = \frac{\langle (\delta N)^3 \rangle}{\langle (\delta N)^2 \rangle^{3/2}}$$

$$\kappa = \frac{\langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2}{\langle (\delta N)^2 \rangle^2} \approx \frac{\chi_x^4}{\chi_x^2}$$

R.V. Gavai and S. Gupta: 1001.2796.
F. Karsch and K. Redlich, arXiv:1007.2581

Skewness: Symmetry of the correlation function.

Kurtosis: Peakness of the correlation function. *Connection to thermodynamics, χ_x .*

Higher order correlations are correspond to higher power of the correlation length of the system: **more sensitive to critical phenomena.**

S & **K** observables:
total charge, total protons,
net-p, net-Q